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# Effects of Air Pollution and Acid Rain on Agriculture: An Annotated Bibliography

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Joseph R. Barse
Walter Ferguson
Virgil Whetzel

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EFFECTS OF AIR POLLUTION AND ACID RAIN ON AGRICULTURE: AN ANNOTATED BIBLIOGRAPHY. By Joseph R. Barse, Walter Ferguson, and Virgil Whetzel, Natural Resource Economics Division, Economic Research Service, U.S. Department of Agriculture, Washington, D.C. October 1985. ERS Staff Report No. AGES850702.


ABSTRACT

Ozone and sulfur dioxide--gaseous air pollutants--can reduce the yields of key agricultural crops such as soybeans, corn, wheat, citrus fruit, cotton, and peanuts by interfering with plant photosynthesis. In general, the greater the pollutant concentration, the greater the yield reduction. Based on this biological evidence, economists are now estimating dollar impacts of ozone pollution on agriculture. By contrast, evidence on the biological impacts of acid rain on crops, soils, and forests is much less clear, often ambiguous. Some acid rain impacts can be favorable, because rainfall acids contain nitrogen and sulfur--major plant nutrients. On balance, acid rain seems to be far less damaging to agriculture (if damaging at all) than the gaseous pollutants. Nevertheless, gaseous pollutants and acidity in rain both originate to a significant degree from the same or similar sources--man's pollutant emissions to the atmosphere.



Keywords: Air pollution, pollutants, acid rain, crops, crop yields, crop loss, soils, forests, ecosystems, economic effects, pollution economics, bibliography.



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## SUMMARY

Some gaseous air pollutants, especially ozone, reduce the yields of key crops, such as soybeans, corn, wheat, citrus, cotton, and peanuts. These pollutants reduce yields because they interfere with the process of plant photosynthesis. Yields are cut by varying degrees, depending on the type and concentration of pollutant in the air, the frequency and duration of exposure, and the phase of crop growth at which exposure occurs. However, sensitivity to air pollutants differs markedly among crops, and even among varieties of the same crop, suggesting that resistance or sensitivity to air pollutants is, in part, genetic.

Based on crop yield reduction data from field experiments, and on observations of regional air quality over a growing season, economists are estimating the actual effects of ambient air pollution on total physical output of a crop, regionally or nationally, for a given year. Economists are also projecting total output of a crop in future years, using pollutant-yield relationships from prior field experiments, and stating assumptions about acreages planted and regional air quality.

In addition, economists are also estimating changes in dollar returns to agricultural producers as well as changes in dollar expenditures by consumers of the commodity. These are changes from what would have happened had there been no pollutant impact on the crop, or a reduced or greater pollutant impact.

At this time, there is only inconclusive evidence that ambient acid rain (as contrasted to gaseous pollutants) might cause a reduction in yields of major crops, or might harm soils or forests on a wide scale. Besides, if acid rain is not so highly acid that it harms plants as the droplets fall to the ground, chemical elements in the rain can actually benefit plants, depending on nutrient balances in soils. Some of the chemical components of the acid rain are major plant nutrients--typically nitrogen and sulfur.

Gaseous air pollutants in concentrations which have occurred over the past several decades may also be partly responsible for some of the damage observed in certain North American and European forests. These gaseous pollutants appear to be considerably more influential than acid precipitation in contributing to forest damage.

There are many complexities here which can affect a scientific appraisal of the impact of acid rain falling on a crop, a forest, or other plant community at any given location. Among these are the degree of acidity of the rain; potential sensitivity of the plants themselves; the sensitivity of soil microorganisms; the kind of soil on which the acid rain falls; which nutrients are the limiting ones in unmanaged soils; and whether, if a managed soil, lime is routinely added to offset the substantial acidity of commercial fertilizers or the natural acidification occurring in many soils. (Both fertilizers and natural processes in the soil may produce far more acid than that added by rain.)



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Thus, acid contributed by rainfall has the potential, on balance, to be harmful, beneficial, or neutral toward soils and plants, depending on specific circumstances. Appraising that balance is a difficult scientific task. At this time, confirmed generalizations about widespread biological effects of acid rain on trees, other plants, and soils seem out of reach; the appraisal has to be situation-specific. Under these circumstances, the work of the economist is much more difficult than when the biological evidence is clear, complete, and consistent.

Although the two kinds of evidence--on acid rain effects and gaseous pollutant effects--are not equally conclusive, it is well to remember that both these forms of air pollution come from essentially the same sources--emissions from fossil fuel combustion.



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# Effects of Air Pollution and Acid Rain on Agriculture:

# An Annotated Bibliography

Joseph R. Barse*
Walter Ferguson
Virgil Whetzel

## INTRODUCTION

There is much current debate over what action to take about acid rain and air pollution. Some viewpoint about the effects of acid rain and air pollutants lies behind each proposal for action. The scientific literature on these effects is already extensive and is expanding further, partly in response to the 10-year research program being coordinated by the National Acid Precipitation Assessment Program (below), including some of the research performed by the U.S. Department of Agriculture. This bibliography summarizes key findings from published scientific research about acid rain and air pollution, including appraisals of economic effects, as these findings relate to agriculture.

The two terms--air pollution and acid rain--are part of the more general and technical term "atmospheric deposition," which includes deposition of gases, particulates, and liquids upon plants, soils, or any other form of life or object on the earth's surface. References in this report are not limited to those dealing with acid rain, but also cover deposition of gaseous and particulate pollutants.

### Scope and Objectives

Some bibliographies tell us what topics are covered by each publication entry, but very little about what the publications have to say on those topics. This bibliography is different, because its main objective is to communicate research findings, in this case on the biological effects of acid rain and other air pollutants on crops, soils, and forests, and the economic effects on crop producers and consumers.

To present these findings, we could have written an interpretive review, weaving detailed conclusions together, citing all the references we cover here. However, we chose the annotated bibliography, rather than the review, in order to stay "as close to the science" and to be as objective as possible. If consensus exists among the researchers, it emerges; if not, the differences are openly displayed. Showing similarities and differences is desirable in a subject matter area such as this one, in which "the science" is far from settled.

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Articles or reports which only advocate a policy position are not included in this bibliography, since it focuses on science, principally biology and economics. Nevertheless, some articles on the implications of various policy options are included because these articles are not overt advocacy and do trace out possible alternative effects on crops of different air pollutant levels.

The scope of this bibliography is limited to entries showing effects of air pollutants on agriculture (broadly defined), because the quantity of all "effects" literature on acid rain and air pollution, including effects on aquatic life and materials, is too large to cover well in one report of this kind. Thus, there is a logic to covering some references and excluding others. The "terrestrial effects" category covered in this report (basically, effects on crops, plants, soils, and forests) is already recognized by the National Acid Precipitation Assessment Program (NAPAP) as one of the nine major categories 1/ of acid rain-related research. Another of these categories, "Assessments and Policy Analysis," (closely related to "effects" research) is covered in part by this bibliography, because we do include some economic reports as well as some analyses of alternative agricultural effects stemming from hypothetical policy alternatives.

However, the other seven categories--"natural sources" (of air pollutants), "man-made sources," "atmospheric process," "deposition monitoring," "aquatic effects," "effects on materials," and "control technologies," are not covered by our bibliographic entries, because the amount of literature is too large, as noted above.

Nevertheless, in order to provide readers some background on the physical processes leading to air pollution, and thus to terrestrial effects, we do include a short review section on the origin and fate of air pollutants. We have tried to limit this background review to reasonably well established general conclusions, avoiding topics still controversial or only partly investigated. Therefore, the origin and fate background is a broad-brush introduction, not intended to review these matters in depth, in contrast to the more detailed, annotated "effects" bibliography, which follows the background section.

## Role of Economic Analysis

Agronomists and plant pathologists are continuing to conduct experiments on the effects of air pollutants and acid rain on crop yields. Is it still too early, then, for economists to try to assess economic effects? Until the agronomists and other physical scientists have finished more research on the effects of air pollution on plants, do economists have anything meaningful to say?

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1/ These effects targets were defined in the mid-1970's by land-grant university scientists working under North Central Regional Project NC-141 to address the question of acidic deposition. This project has now evolved into the National Atmospheric Deposition Program (NADP), a joint Federal-State undertaking. Thus, State-sponsored efforts preceded the NAPAP national research activities. For a full description of NAPAP, see the National Acid Precipitation Assessment Program Annual Report, 1983, to the President and Congress, NAPAP, 722 Jackson Place, Washington, D.C. 20503. Research being conducted by the 13 Federal agencies participating in NAPAP is being addressed to the gaps and uncertainties in knowledge about acidic deposition and its effects. A final NAPAP report assessing the state of knowledge about acid rain and drawing scientific (not policy) conclusions is scheduled for 1989, with interim reports in 1985 and 1987.



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Even before definitive biological data are available, economists can get preliminary data on biological impacts of pollutants on crops. Then, these preliminary data can be employed in economic models to determine the theoretical sensitivity of the economic system to the various levels of hypothesized crop damage. Such a "sensitivity study" is one way to explore whether there is a possibility of an economic problem and to place some tentative bounds on the scope of this problem.

In addition, economists, agronomists, and plant pathologists may find it helpful to interact at all phases of research in air pollution impacts. Each discipline may have something to contribute to and learn from the other as research activities are planned and progress. The idea that economics must wait until all experimental results in agronomy are agreed upon and complete is not useful.

In any case, based on our survey of professional literature, economists are already conducting analyses of several kinds. Agronomists and others have published many reports, including much basic data on the response of commercially important crops to air pollutants. Many experiments are continuing, and data will improve, but at the very least some data on crop response are adequate for economists to use at the present time. Economists no longer have to rely only on hypothesized crop damage from air pollutants, but now have some well-documented crop damage data to use in economic analyses. An early generation of reports on economic effects of air pollutants on crops is now in print. Other reports are expected to follow.

Economists are estimating what the economic impacts seem to be from reduced crop yields attributable to plant response to air pollutants or acid rain. Or, put another way, if air pollution and/or its adverse effects on crops were abated or mitigated, would producers or consumers of these crops be better off economically? By how much?

Although the body of scientific experiment literature points definitely to a reduction in yield of some key agricultural crops from polluted air, it does not always follow that pollution abatement or mitigation would make farmers and/or consumers better off. The prospect of economic gain is there, but uncertain. Uncertainty stems from the basic economic nature and complexity of the food and fiber sectors, characterized by wide price fluctuations and market risks on all sides. Nevertheless, economists do have useful things to say about the specific circumstances in which mitigating or eliminating adverse crop response to pollutants can lead to economic benefits.

After all, similar kinds of problems have been addressed by agricultural economists for many years. Economists have estimated the economic impacts of higher yielding varieties and have calculated the economic effects of controlling crop damage from insects, weeds, fungi, or rodents. (For example, see Osteen, Craig B., Edward B. Bradley, and L. Joe Moffitt, The Economics of Agricultural Pest Control: An Annotated Bibliography, 1960-1980. Economics and Statistics Service, USDA, January 1981.) Although living pests and chemical air pollutants are different damage agents, there may be strong similarities in the economic analysis of abating damage from either source. The methods and findings of existing economic analysis of air pollutant damage to agriculture are summarized in the bibliographic entries of this report covering economic effects.



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## Organization and Style

In the section immediately following, we review highlights of recent research findings on air pollutants. This review is a necessary background for the more detailed report-by-report summaries of biological effects of air pollutants, which in turn are the background for economic analyses.

We do not attempt to create a synthesis of the literature on biological or economic effects, thus allowing as much "flavor" as possible of individual, sometimes diverse, findings to come through. In many cases, we have therefore quoted extensively from the references cited, where this seemed the best way to communicate the findings. We do not claim to have included every relevant reference. But, acknowledging that there are bound to be gaps in our selection, we can only ask readers to help us fill in these gaps by calling them to our attention.

Within each of the sections on crops, soils, and forests, we list first those articles or other publications which tend to survey or review the field (secondary literature), and list next individual studies or field experiment reports (primary literature). This does not imply that either the primary or the secondary literature is the more significant, but is just one way to organize the material.

In a separate section, the references are also listed alphabetically, numbered sequentially, and cross-referenced to the prior page of the report on which the reference summary or citation appears. Because this report necessarily includes some technical terminology from various disciplines, there is a glossary, which appears after the alphabetical listing of bibliographic entries. In addition, there is an index of plants mentioned in the various entries, showing the page where the mention appears. Finally, there is also a page index which classifies bibliographic entries into two categories, those which refer to impacts of ozone or other gaseous pollutants, and those which refer to impacts of acid rain. Some entries fall into both categories.

# BACKGROUND: ORIGIN AND FATE OF AIR POLLUTANTS

Background information on air pollutants can be of help in understanding the literature which appraises the effects of these pollutants on crops, soils, and forests. Some air pollutants, as gases, can harm agricultural crops, while others are precursors of acid rain, also a potential damage agent.

## Primary Pollutants

Among the major air pollutants are: sulfur dioxide, nitrogen oxides, carbon monoxide, nonmethane hydrocarbons--all as gases--and various kinds of particulates, including heavy metals such as lead. These are "primary" air pollutants because they tend to be the immediate residuals released to the atmosphere from emissions sources on earth. The gaseous primary pollutants may then become "raw materials" for atmospheric processes which transform them chemically.

There are numerous natural sources of primary pollutants, including volcanoes, forest fires, and desert dust storms. But soils, too, emit and remove volatile gases, as do forests and grasslands. Engines and furnaces which burn fossil fuels are among the sources created by humans. Primary pollutants emitted from



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Europe and North America are probably mostly human-generated rather than natural, but whether the same is true on a global basis is a different question, not addressed here. The point, though, is that humans' pollutants are additive to those of nature. When pollutants are measured in the atmosphere by instruments, those created by humans are usually distinguishable from the natural background pollution level. Moreover, scientists now suspect even this natural background level to contain pollutants emitted by human sources and remaining in the atmosphere for very long periods (K, p. 127).1/

Urban areas are major sources of gaseous primary air pollutants, although rural power plants and industries are also measureable point sources. Atmospheric hydrocarbons and oxides of nitrogen originate principally from the burning of fuels in internal combustion engines, electric power plants, industrial plants, and residences. Sulfur dioxide originates principally in the combustion of sulfur-containing coal (or oil) by electric utilities and other industries. Unburned volatile hydrocarbons from gasoline engine exhausts (incomplete combustion), and vapors from gasoline service stations or chemical plants also are important sources of primary pollutants.

In the United States in the 1970's, about 28 million tons of sulfur dioxide per year were being emitted from human-generated sources, and about 22 million tons of nitrogen oxides (I, p. 2). There is great variability around the Nation county-to-county and even region-to-region in the density of emissions of both sulfur dioxide and oxides of nitrogen. There are especially high emissions of sulfur dioxide in the Ohio River Basin, for example, and of nitrogen oxides in the Boston-Washington corridor (A, p. 41).

## Atmospheric Transformation and Secondary Pollutants

Primary air pollutants, after emission, may be transformed chemically in the atmosphere to compounds which, for convenience, are called "secondary pollutants."2/ Among the secondary pollutants are: ozone, nitrogen oxides (both primary and secondary), nitric acid, sulfuric acid, nitrates, sulfates, and ammonia. These and others may be formed in the atmosphere by complex chemical processes reasonably well-understood by scientists, but not yet fully quantified.

In the daytime, these processes are in part photochemical, driven by sunlight. When primary or precursor pollutants such as sulfur dioxide and nitrogen dioxide mix with each other and with hydrocarbons--plus oxygen and hydrogen already present--and are then irradiated by sunlight, the photochemical and other reactions may lead to production of ozone (termed a "photochemical oxidant"), acids,

1/ Capital letters in parentheses refer to references cited on pages 12 and 13.

2/ Some of these secondary compounds as gases or tiny liquid droplets may be formed in the exhaust pipe or stack itself by rapid chemical action just before the combustion residues reach the atmosphere. Moreover, after emission large portions of the primary pollutants may remain in the atmosphere unconverted to secondary compounds for days, and some usually sink to earth still in their primary state. Thus, the instant of emission is related to but does not define exactly the difference between primary and secondary pollutants. The primary pollutants are starters for chemical process, while secondary pollutants are intermediates or results.



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and nitrate and sulfate aerosols.3/ Thus, secondary pollutants are formed by reactions which continue over hours or days in a gaseous/aerosol system. Reactions other than photochemical continue into the night. Functional relationships determining the rates of formation of the different pollutants and other variables are still being explored by scientists. The relationships in atmospheric chemistry are extremely complex (A, pp. 155-195).

For example, there is no simple formula to determine the rate at which sulfur dioxide is converted to sulfate or sulfuric acid; some observations suggest that only 20 to 50 percent of the sulfur dioxide gas may be expected to be converted to sulfate aerosol or acid (E, p. 85). Another example: No easy generalization is possible as to which compounds--sulfur or nitrogen--will dominate a mass of polluted air. It is an empirical question.

For agriculture, ozone is an especially significant pollutant because, in high concentrations, it can reduce the yields of commercially important crops. (See summaries of various bibliographic references in this report.) In urban air, where primary pollutants are abundant, ozone may form, break up and re-form in cyclical reactions started and driven by the action of sunlight on nitrogen dioxide. These reactions lead to both ozone and nitric oxide, which may also originate as a primary pollutant, directly from combustion. Continuing the cycle, ozone may then react with the nitric oxide to re-form nitrogen dioxide. Only small, steady concentrations of ozone result from this cycle. But, when hydrocarbons are also present, they too react with nitric oxide, converting it directly to nitrogen dioxide, leaving less nitric oxide to react with ozone. In this case--where hydrocarbons are abundant--ozone increases to much larger concentrations (K, pp. 14-27).

As an air mass containing considerable nitrogen dioxide and hydrocarbons moves away from a large city and no longer receives incoming quantities of nitric oxide pumped into the air from, say, vehicle exhausts, ozone production may then rise greatly. This is because new nitric oxide breaks up ozone; lacking the breakup agent, sunlight boosts ozone output in polluted air (K, pp. 130-131, 145).

Thus, ozone precursors released near the city may combine downwind from the city, over the countryside, to produce major ozone concentrations. In rural areas, when ozone concentration rises, it can stay high for long periods (K, p. 146; L, p. 386).

In the same air mass in which ozone forms, sulfate (and probably nitrate) aerosols may be forming as well. Although there is no scientific consensus yet on the exact details of the oxidation chemistry by which aerosols form, much has been learned about air pollutants since the pioneering studies in the early 1950's of Los Angeles smog, an aerosol/gas combination. The formation of ozone and aerosols is frequently linked, because sulfur dioxide from power plants

3/ Aerosols are liquid droplets or tiny solid particulates in the atmosphere, ultra-fine to fine in size, ranging in diameter from .002 microns to about 50+ microns. By contrast, dust particulates tend to be above 50 microns, and are termed coarse aerosols. Coarse aerosols--such as desert dust--typically are formed by breakup of larger particles, while the finer aerosols are formed by condensation of gases or by accretion of liquids around a fine or ultra-fine nucleus (G).



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mixes with nitrogen oxides and hydrocarbons from urban areas to make a vast chemical "soup" in the atmosphere. Add sunlight and high temperatures and many reactions begin taking place simultaneously. The chemical hydroxy and peroxy radicals appear to play an important role linking the production of acids, nitrate/sulfate aerosols and ozone into an interconnected series of reactions (D, p. 281).

Sulfate and nitrate aerosols in an air mass reduce visibility and produce haze, because light is scattered by the fine droplets or particles. Moreover, these aerosols are precursors of acid rain if a thunderstorm occurs in the polluted air mass, or if parts of it are drawn into a low pressure system producing widespread rainfall.

While still airborne, sulfur dioxide, sulfates, nitrogen oxides, and nitrates combine with oxygen and hydrogen to produce atmospheric ammonia and sulfuric and nitric acids, the two main acidic components of acid rain. The combination of these sulfur and nitrogen compounds with hydrogen ions takes place via several atmospheric processes: photochemically as vapors or gases, and through solution chemistry in cloud or rainwater or on water films on solid cores of fine particulate aerosols. The hydrogen ions come from atmospheric water as vapor or liquid, as well as from other atmospheric sources of hydrogen, both pollutant and natural.

## Mixing and Long-Range Transport

As recently as the 1960's, there was little reason to believe that air pollution was anything other than a series of unconnected local events. Many people thought that air pollutants emitted from an industrial complex or a city would quickly fall to earth nearby or disperse, lose their identity, and become so diluted as to be an indistinguishable part of natural background air not far downwind from the pollutant source. However, the image of air pollution as purely local has now been thoroughly shattered by the wave of atmospheric observations, experiments, and projects begun in the 1970's.

Both the pollutant gases and the ultra fine and fine aerosols are capable of suspension or "residence" in the atmosphere for many hours or days. Thus, these gases and aerosols, once aloft, are very susceptible to being picked up by a wind/weather system and transported on direct or circuitous courses for hundreds or even thousands of miles before falling on land or into the sea. Mixing and long distance transport of air pollutants from multiple sources has now been confirmed by many research projects and observations (A, pp. 30-35; L, p. 379).

Air sampling from aircraft and aerial photographs show that combustion residuals can frequently be observed streaming downwind as "plumes" from the stacks of electric power plants for more than 100 miles (C, p. 202). In fact, the mass of pollutants emanating from an entire urban area may also form a clearly detectable "urban plume." For example, the St. Louis urban plume has been sampled and tracked for over 100 miles in various directions on different occasions (C, pp. 202-217).

As plumes widen and disperse downwind under the influence of crosswinds or other air circulation patterns, these plumes and pollutants from a dozen or more cities and nonurban power plants may mix into a regional air mass. With current detection technology, it is exceedingly difficult or impossible to trace the contri-



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bution of a city or a specific power plant to the regional air pollutant mass. For example, scientists observing high ozone concentrations over both rural and urban Wisconsin in 1974, also noted weather patterns and air flows leading up to the high ozone event. They concluded that far-distant, middle-distant, and local sources were all responsible, but the scientists could not apportion the observed ozone among the various sources (H, p. 418).

Ozone and other secondary pollutants form very actively in urban plumes which are not immediately dispersed by winds. Where plumes remain identifiable over long distances, emissions carried to the farthest extent may have been airborne for a day or more; during this time the mass of primary pollutant gases has continued to oxidize and undergo other chemical change so that major fractions of each of these primary pollutants have been modified into secondary pollutants. Secondary pollutant levels in such plumes typically are sharply higher than in surrounding ambient, background air (C, p.217). However, as the plume mixes with those of other urban areas, concentrations of pollutants in the resulting mixture may continue to remain high.

Under the influence of summer solar radiation and heat, these pollutant mixtures frequently form vast veils of haze over much of the eastern United States and Canada. These hazy air events are the result of sharply elevated levels of sulfate and other aerosols, which scatter sunlight and greatly reduce atmospheric visibility. High levels of these aerosols are reasonably well correlated (though not perfectly) with high levels of ozone and other photochemical oxidants, since both the aerosols and the oxidants are products of the same general chemical processes producing secondary pollutants.

## Episodes of Persistent Elevated Pollution

Time-lapse imagery from earth satellites offers dramatic visual evidence of the formation, circulation, length of life, and dispersal of these vast "blobs" of haze over the North American continent and the North Atlantic Ocean.

For example, in late June 1975 a large smog blob formed from Kentucky and the Ohio River Valley west over Missouri to Kansas, and from Louisiana and Texas north. During June 25-July 5, 1975, time-lapse images transmitted by the satellite SMS/GOES 4/ show this vast blob circulating clockwise, as in a slow-motion movie, around a stagnant high pressure area centered over Michigan (H, p. 427-428).

Within the haze as it circulated, sulfate readings were high--up to 80 micrograms per cubic meter--as contrasted to much lower readings outside the blob, 15 micrograms or less. Ozone monitoring sites reported high 1-hour maximum averages in and near the haze (H, p. 427-428). The persistent high pressure area blocked direct northeastward movement of the pollutants from the Midwest, causing them to accumulate and then to be advected west and north into the clockwise circulation pattern around the high.

These hazy, persistent high pollution episodes lasting a week or 10 days are characteristically associated with circulation around or stagnation behind a summertime high in the Midwest, Southeast, and East. In that quarter of the

4/ Synchronous Meteorological Satellite/Geostationary Operational Environmental Satellite



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continent, urban areas are spaced so closely that intervening rural areas may remain for days under the influence of a mass of well mixed secondary pollutants from several urban plumes.

During a persistent pollution episode in which atmospheric circulation stagnates over some area, urban plumes feeding into that circulation will keep pumping in pollutants, raising concentrations still further. Although hazy, low-visibility air is strongly correlated with high sulfate concentrations, it is less strongly related to ozone concentrations because these are influenced also by local sources of nitrogen oxides. Ozone thus exhibits greater spatial variability than sulfates, with or without an elevated pollution episode.

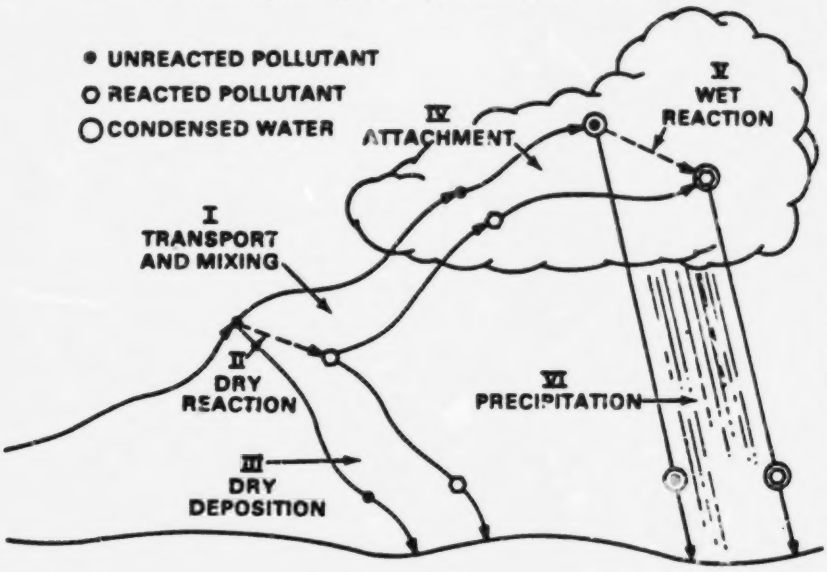
These episodes may occur several times during a summer in the eastern half of the country, although the Los Angeles area and other parts of the Nation also experience high pollutant levels frequently. As an episode occurs, the entire countryside below may be blanketed by pollutant gases for days on end during the crop growing season. If pollutant gas concentrations are high enough for a long enough period of time, invisible damage to agricultural crops--in the form of reduced yields--will probably occur. (See later references in this report.)

## Deposition Processes and Data

Air pollutant gases or particulates frequently fall back to earth in dry form, without ever being combined with atmospheric liquid droplets. However, gases or particulates, once on the surface or on any object on the surface, may combine with surface moisture, such as a body of water or drops on a leaf. Of course, these gases and particulates also join in the atmosphere with water drops or pollutant aerosols (such as dilute sulfuric acid droplets) and then return to earth in wet form as rain, snow, fog, or mist.

Although the terms "wet deposition" and "dry deposition" can be illustrated easily in a diagram (fig. 1), these terms actually encompass several detailed and complicated deposition processes (A, p. 30). Wet deposition has tended to receive more scientific attention than the dry processes, at least until recently. The wet deposition processes have been and are being studied with extra intensity by scientists because of widespread concerns about acid rain (A, pp. 1-6). Studies focus both on the physical atmospheric processes by which precipitation forms and falls, "scavenging" air pollutants, and on the

FIGURE 1. Atmospheric pathways leading to acid deposition.



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chemical reactions which occur as the pollutants mix with formative raindrops, making the rain or snow more acid than it would be naturally. 5/

Acidity is measured by the concentration of excess or unneutralized hydrogen ions in a solution. The greater the hydrogen ion numbers, the greater the acidity to the extent that hydrogen ions exceed (are not neutralized by) "basic" ions of calcium, magnesium, or other alkaline substances. The pH scale, which measures acidity, is constructed so that the smaller the number on the scale below pH 7.0 (neutral, neither acid nor alkaline), the greater the concentration of excess hydrogen ions. Each whole number on the pH scale represents a tenfold difference in excess hydrogen ions. Thus, vinegar, which is rated at pH 3, is 10 times more acid than a rain sample at pH 4, 100 times more acid than a sample at pH 5, and a thousand times more acid than a rain sample testing at pH 6.

It is ironic that the air pollutants we focus on--sulfur and nitrogen--are not in acidic forms when they go up, nor even when they combine with oxygen. Sulfur and nitrogen only become acidic when, still aloft, they also combine with hydrogen as gases or liquids. Converted to acids in the atmosphere, the sulfur and nitrogen are thus "ripe" to fall back to earth in solution with rainwater, making its pH value more acidic than that of natural rain in many cases.

However, the strength of this atmospheric acid will also depend on how many ions of basic, acid-neutralizing aerosol particulates may have combined with the acid while still in the air. Wind-blown dust often carries basic ions of calcium and magnesium, which can become the alkaline particulate cores of fine aerosols, attracting and partially neutralizing a liquid acid film. In fact, some rainfall samples show pH values over 6, less acid than the theoretical pH 5.6 value of natural rain. Thus, precipitation acidity may or may not be modified in the air, even as it may or may not be modified after it falls to earth, depending on the receiving substance.

Both the chemical composition of rainfall and the degree of acidity vary widely over time and space. Rainfall samples from the extensive U.S.-Canadian collection network report this composition and acidity in detail, along with other variables, including precipitation amounts (B, J). Data from monitoring stations show the amounts of calcium, magnesium, potassium, sodium, ammonium, nitrate, chloride, sulfate, phosphate, and hydrogen present in the rainfall samples, collected weekly. At the station in Cheboygan County, Michigan, for example, amounts of nitrate in 11 weekly samples varied from a low of 0.77 milligrams per liter to a high of 4.05 milligrams during late 1981, while the acidity of the same samples ranged from pH 5.41 to pH 4.26. The most acid sample was therefore over 10 times more acidic than the least.

When one examines a map summarizing gradations in annual average rainfall acidity (fig. 2), it is well to keep in mind the variability of the data on

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5/ On the pH scale of acidity, what is the pH value of "natural" precipitation? A neutral (neither acid nor alkaline) value is 7.0, but the value of distilled water droplets in the presence of pure atmospheric gases becomes pH 5.6 because of the acidifying influence of carbon dioxide. Then, allowing for the further acidifying or alkalizing influence of natural pollutants, some scientists would define the range of "natural" precipitation anywhere between pH 6.5 and pH 4.9 (A, p. 13).



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FIGURE 2. Annual mean value of pH in precipitation weighted by the amount of precipitation in the United States and Canada for 1980. Source: (A).

which the map is built. Moreover, while the rainfall acidity map is showing principally the hydrogen, the sulfur and nitrogen which mobilized this hydrogen were also deposited. Since nitrogen, sulfur, and other constituents of rainfall are plant nutrients, one should not focus an analysis of the effects of acid rain solely on on the impacts of the hydrogen ions, but should consider the overall effects of all rainfall constituents. Many of the subsequent bibliographic references in this report do so.

Although the National Atmospheric Deposition Program (NADP) is now reporting excellent data on acid deposition, long-term time series data are scarce. The NADP and the Canadian (CANSAP) networks began operating only in 1978.

Reliable nationwide, or even regional data do not go back far enough in time to establish whether or not there is a trend of rising acidity in rainfall since, say, 1950. Nevertheless, there is a presumptive case that since, say, the year 1750, the rise in the use of fossil fuels has caused precipitation in industrial areas today to be more acid than 200 years ago. Thus, there is likely a very long-term trend to rising precipitation acidity in eastern North America. The NADP/CANSAP data may, in a few years, comprise a long enough time series to permit the first estimate of whether there has been a trend to increasing acidity since 1978.

Obviously, the variability in NADP/CANSAP rainfall samples is determined both by the formation of compounds in the atmosphere and by the meteorological processes which cause the rain. The results of wet deposition are readily measured. By contrast, there is still great difficulty is measuring the quantities of dry deposition of pollutant gases. Consequently, in attempting to measure gaseous dry deposition, we are left with a proxy for deposited amounts, namely, the concentration of gas in the air.

Dry deposition may be just as important as wet deposition as a means of depositing acids or acid-inducing material (such as gases, sulfates or nitrates) on the earth's surface. Some scientists suggest that dry deposition could account for about the same amount of human-generated additional acid as rain, mist, and snow. If so, the collection of data on acid deposition becomes more complicated than



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collecting rainfall samples alone. The surface acid from pollutants thus may include not only that formed in the atmosphere, and then deposited, but also that formed after deposition, by contact of gases or particulates with surface moisture (A, p. 232). While this is certainly one convincing rationale to conduct more studies on dry deposition, it is not the only one, because dry deposition of pollutant gases also appears to have a direct effect on photosynthesis in several plant species important to agriculture (see bibliographic entries).

The amount of a pollutant gas transferred from the air to surface vegetation is certainly related to the concentration of the gas in the air just above. However, gas concentration is only a first approximation of the amount deposited; one must also consider the deposition "velocity," in turn related to variables such as atmospheric turbulence and resistance, leaf stomatal and cuticular resistance; roughness of the vegetation canopy; and an array of factors influencing the ways plants use gases in photosynthesis (A, pp. 70, 214).

Actually measuring dry deposition of gases, however, is extremely difficult compared with measuring wet deposition. Until better means of measurement are worked out, gas concentrations in the air over vegetation will have to serve as the best available approximations of deposition.

Much of the data on concentrations of gaseous pollutants come from observations in urban areas. Nevertheless, some rural area data are available (A, pp. 15, 46, 151; K, pp. 128-133, 145-150). In addition, the TOMS instrument aboard the Nimbus 7 satellite is capable of mapping ozone concentrations over wide areas, although whether the TOMS data have sufficient resolution to be useful for rural air pollution studies is problematical. 6/

The foregoing will be useful background information as the reader reviews the annotated references on the effects of air pollutants and acid rain in the remainder of this report.

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6/ TOMS is the total ozone mapping spectrometer. The data from this instrument are comparable to those from Dobson spectrophotometer stations, a conventional method of measuring ozone on the surface, but TOMS data have resolution of an area only 50 x 50 kilometers at best, over which ozone is averaged for the entire atmospheric column from the earth's surface to the upper stratosphere. Therefore, both lower atmosphere and upper atmosphere ozone are included by TOMS (F, p. 1377).

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(B) Canadian Network for Sampling Precipitation (CANSAP). Monitoring Reports.

(C) Ellestad, Thomas G. "Aerosol Composition of Urban Plumes Passing Over a Rural Monitoring Site," Aerosols: Anthropogenic and Natural, Sources and Transport. Ed. T. J. Kneip and P. J. Lioy. Annals of the New York Academy of Sciences, Vol. 338. Proceedings of a conference held January 9-12, 1979,




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(D) Gillani, Noor V. and William E. Wilson. "Formation and Transport of Ozone and Aerosols in Power Plant Plumes," Aerosols: Anthropogenic and Natural, Sources and Transport. Ed. T. J. Kneip and P. J. Lioy. Annals of the New York Academy of Sciences, Vol. 338. Proceedings of a conference held January 9-12, 1979, cosponsored by the New York Academy of Sciences and the Air Pollution Control Association. New York, 1980. 276-296.

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(F) Krueger, Arlin J. "Sighting of El Chichon Sulfur Dioxide Clouds with the Nimbus 7 Total Ozone Mapping Spectrometer," Science, 24 June 1983. 1377-1379.

(G) Lippman, Morton. "Size Distributions in Urban Aerosols," Aerosols: Anthropogenic and Natural, Sources and Transport. Ed. T. J. Kneip and P. J. Lioy. Annals of the New York Academy of Sciences, Vol. 338. Proceedings of a conference held January 9-12, 1979, cosponsored by the New York Academy of Sciences and the Air Pollution Control Association. New York, 1980. 1-12.

(H) Lyons, Walter A. "Evidence of Transport of Hazy Air Masses from Satellite Imagery," Aerosols: Anthropogenic and Natural, Sources and Transport. Ed. T. J. Kneip and P. J. Lioy. Annals of the New York Academy of Sciences, Vol. 338. Proceedings of a conference held January 9-12, 1979, cosponsored by the New York Academy of Sciences and the Air Pollution Control Association. New York, 1980. 418-433.

(I) National Air Pollutant Emissions Estimates, 1970-78. EPA document 450/4-80-002. U. S. Environmental Protection Agency, Washington, D. C., 1980. Page 2.

(J) National Atmospheric Deposition Program. NADP Data Report: Precipitation Chemistry, Vol. III, No. 4, 1980. Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, Colorado, 1981.

(K) Ozone and Other Photochemical Oxidants. Report of the Committee on Medical and Biologic Effects of Environmental Pollutants, National Research Council, National Academy of Sciences. Washington, D. C., 1977.

(L) Wolff, George T. "Mesoscale and Synoptic Scale Transport of Aerosols," Aerosols: Anthropogenic and Natural, Sources and Transport. Ed. T. J. Kneip and P. J. Lioy. Annals of the New York Academy of Sciences, Vol. 338. Proceedings of a conference held January 9-12, 1979, cosponsored by the New York Academy of Sciences and the Air Pollution Control Association. New York, 1980. 379-388.



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ANNOTATED BIBLIOGRAPHY, BY TOPIC

## Effects on crops and plants (except trees)

### Surveys and reviews

Council for Agricultural Science and Technology (CAST). Acid Precipitation in Relation to Agriculture, Forestry, and Aquatic Biology. Report of the CAST Multidisciplinary Task Force on Acid Precipitation. CAST Report No. 100, June 1984. Ames, Iowa.

"The ill effects of acid deposition and polluted air on plants and soils near some sources emitting large amounts of sulfur dioxide are well known. Simulated acid rain has been shown to decrease the yields of some crops within the pH range of acid rain measured under field conditions and to injure crop foliage when the acidity is greater than that usually found in the most acid rain. Unfavorable effects of acid deposition on domestic animals, crop yields, and foliage of plants grown in the field at locations remote from local sources of large amounts of gaseous pollutants, however, have not been demonstrated. Some of the chemical elements in acid deposition (sulfur and nitrogen are the ones of greatest importance) are essential nutrients for both plants and animals and are supplied in fertilizers to correct deficiencies in plants.

"The amounts of acidity developed in cropped soils as a result of natural processes and management practices considerably exceed the amounts received from acid precipitation. For this reason as well as the common practice of applying crushed limestone to neutralize soil acidity, it is concluded that acid deposition will not have a measurable effect upon the acidity of cropland."

Cowling, Ellis B. "Acid Rain in Perspective: The Path from Research to Public Policy," Acid Precipitation: The North American Challenge. Proceedings of a conference held October 25-28, 1982 in Burlington, Vermont. Soil Conservation Society of America, Ankeny, Iowa, 1983. 2-1 to 2-30.

"Precipitation with an average annual pH below that which is expected from natural rainfall (pH 4.8 to 6.5 according to Charlson and Rodhe, 1982) is occurring over large regions of the North American continent....The major known detrimental effects of ambient acid deposition are restricted to certain sensitive aquatic ecosystems....The major sensitive regions in North America....usually are recently glaciated, with large areas of exposed granitic (crystalline) and other noncalcareous bedrock and thin soils that are low in acid-neutralizing and cation-exchange capacity....

"At present there is no compelling evidence that the effects of ambient acid deposition on terrestrial ecosystems are more detrimental than beneficial. Mainly on the basis of controlled exposures of crop plants



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and forest trees to simulated acid deposition, we have good reason to be suspicious, but no compelling evidence with which to conclude, that forest and agricultural ecosystems are presently being harmed by ambient acid deposition....

"In various regions of North America, economic damage to forests and agricultural crops is occurring as the result of dry deposition of toxic gases. Ambient concentrations of ozone, sulfur dioxide, and oxides of nitrogen, acting alone or in combination, are causing important damage and decreases in yield of both crops and forests. For two major reasons this demonstrated harm to crops and forests by toxic gases should be considered both together with and separately from the well-demonstrated effects of acid deposition on aquatic ecosystems: (a) Sulfur and nitrogen oxides are the very same substances that serve as chemical precursors of atmospheric ozone and other photochemical oxidants, respirable particulate matter, atmospheric haze, and/or acid deposition; and (b) mixtures of ozone, sulfur dioxide, and nitrogen oxides, as well as mixtures of ozone and acid precipitation have been shown to induce greater harm to various plants than these pollutants acting alone."

Heck, Walter W., Richard M. Adams, William W. Cure, Allen S. Heagle, Howard E. Heggestad, Robert J. Kohut, Lance W. Kress, John O. Rawlings, and O. Clifton Taylor. "A Reassessment of Crop Loss from Ozone," Environmental Science and Technology, Vol. 17, No. 12, December 1983. 572A-581A.

"NCLAN [National Crop Loss Assessment Network] consists of a group of government and nongovernment organizations cooperating in field research, crop production modeling, and economic studies to assess the immediate and long-term economic consequences of the effects of air pollution on crop production. The nationally coordinated field studies are designed to provide crop dose-response data that are as free of artifacts as is possible using state-of-the-art technology....

"Estimated production losses [percentage yield reductions] to major crops from ozone at seasonal 7-hr/day mean ozone concentrations of 0.04 to 0.06 ppm (when compared to a base concentration of 0.025 ppm) were: soybean, 7.9 to 18.6%; field corn (2 cultivars), 0.6 to 3.1%; soft red winter wheat, 0.08 to 3.6%; California irrigated cotton, 6.6 to 15.2%; and peanut, 7.0 to 19.7%. The data presented are valid for the particular cultivars and conditions under which they were obtained. Care should be taken in extrapolating the data beyond the conditions under which they were generated. This article represents the second NCLAN assessment of yield losses. It is a limited assessment and uses an empirical economic assessment. This initial economic assessment was limited to a five-state region to test an economic model that used selected crop loss functions for soybean, corn and wheat, the available ozone air quality data, and crop production figures....



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"The NCLAN program will continue to develop yearly assessments of the effect of ozone on crops using improved data bases and crop loss functions. The program recognizes the need to incorporate the effects of cultivar susceptibility and soil moisture into the functional relationships."

Heck, Walter W., O.C. Taylor, Richard Adams, Gail Bingham, Joseph Miller, Eric Preston, and Leonard Weinstein: Research Managment Committee for the National Crop Loss Assessment Network. "Assessment of Crop Loss from Ozone," Journal of the Air Pollution Control Association, Vol. 32, No. 4, April 1982. 353-361.

"Past research has shown that ozone ($O_3$) alone or in combination with sulfur dioxide, and nitrogen dioxide is responsible for up to 90 percent of the crop losses in the U.S. caused by air pollution. A previous estimate of direct crop losses, using limited available data and assuming that all areas of the U.S. just met the current ozone standard (0.12 ppm for one h), showed a loss of between one and two billion dollars (2 to 4 percent of crop production). The National Crop Loss Assessment Network (NLCAN) was set up to determine more accurately crop loss from these air pollutants."

"The NCLAN consists of a group of government and nongovernment organizations cooperating in field work, crop production modeling, and economic studies to assess the immediate and long-term economic consequences of the effects of air pollution on crop production....The program is also designed to advance the understanding of cause-effect relationships with the intent of developing simulation models."....

"The basic exposure technique utilizes open-top chambers. These chambers have been well tested and permit control of gas(es) around the plant canopy, allowing specific pollution regimes to be imposed on experimental plants. The chambers ordinarily have little effect on the crops growing within them."

"In 1980 the NCLAN program used open-top field chambers at four regional sites. All sites used a series of five ozone concentrations that were replicated four times with a different crop at each site (Northeast-red kidney bean, Southeast-peanut and turnip, Central States-soybean, Southwest-head lettuce). Dose-response data were developed for each crop. Ambient (AA) ozone concentrations caused observed yield reduction in soybean (10 percent), peanut (14 to 17 percent), a single turnip/cultivar (7 percent), head lettuce (53 to 56 percent), and red kidney bean (2 percent) when the natural background ozone concentrations (seasonal 7-h/day mean) was selected at 0.025 ppm and was considered the control value. Yield reduction was observed in all crops at seasonal 7-h/day (0900-1600 h standard time) mean ozone concentrations of 0.06 to 0.07 ppm when compared with the 0.025 ppm control value."



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Heggestad, H. E. and W. W. Heck. "Nature, Extent, and Variation of Plant Response to Air Pollutants," Advances in Agronomy, Vol. 23, 1971. 111-145.

The major pollutants (ozone, PAN, sulfur dioxide, fluoride and nitrogen dioxide) to varying degrees cause injury to plant cells, interfere with plant growth, and damage plant parts, such as seeds, which can have economic value. "Ozone is now rated by many as the most important pollutant affecting vegetation....Air pollution problems have increased because of multiple sources and mixtures of pollutants. There is increased concern about chronic injury and reduced growth attributed to air pollutants, such as photochemical oxidants and sulfur oxides. Response to pollutants may be altered by many factors, such as genetic, environmental, cultural conditions, time-concentration relationships, and the presence of mixtures of pollutants. The identification and use of tolerant varieties, including resistant varieties developed by breeding, will help reduce losses and assure maximum agricultural production."

Hindawi, Joseph I. "Air Pollution Injury to Vegetation," National Air Pollution Control Administration Publication No. AP-71, U.S. Department of Health Education and Welfare, Public Health Service, Environmental Health Service, National Air Pollution Control Administration, Raleigh, North Carolina, 1970.

The author discusses the sources, symptoms, vegetation affected and injury thresholds for several pollutants including ozone, peroxyacetyl nitrate (PAN), nitrogen dioxide, sulfur dioxide, hydrogen fluoride, chlorine, and ethylene. Plants are considered to be sensitive tools by which the presence of several airborne toxicants in low concentrations can be detected and evaluated. Caution must be taken to differentiate between pollution symptoms and problems associated with mineral deficiency, plant disease and other agents.

International Electric Research Exchange, Working Group II. Effects of $SO_2$ and Its Derivatives on Health and Ecology: Volume 2, Natural Ecosystems, Agriculture, Forestry and Fisheries. Electric Power Research Institute, Palo Alto, California, 1981.

"Chapter 3--Evidence for direct effects of sulfur dioxide on agriculture and forestry"...."Reduction in net photosynthesis (based on $CO_2$ uptake can be detected within a few minutes and reaches a maximum after 1-2 hours on single exposures to elevated levels of $SO_2$. Recovery generally occurs within a few hours after cessation of exposure if no visible injury is sustained. Hence, yield reduction resulting from a single exposure below the visible injury threshold is not likely to be detectable in the field."



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"Evidence for reduced yield resulting from repeated exposures below the visible injury threshold is conflicting. Near point-sources, where short term concentrations (15 minute to 1 hour averages) fluctuate widely through the growing season, yield reduction is more dependent on peak concentrations than on annual average values. On the basis of limited evidence, yield losses of around 10% may be expected for some annual crops in situations where 1 hour average $SO_2$ levels exceed 700 ug/$m^3$ for 2.5% of the time. The corresponding concentrations for some perennial crops such as trees or fruit bushes lie in the range 450 to 700 ug/$m^3$."

"Yield loss without visible injury resulting from continuous exposure to constant $SO_2$ levels has been observed after many weeks or months in chamber studies. For certain grasses and legumes, continuous exposure to 180g/$m^3$ or higher for most of the growing season generally produces significant yield reductions. Other crops and even some grass cultivars are more resistant. Species ranking based on $SO_2$ induced yield losses and visible injury are not necessarily the same."

"There is suggestive, but not conclusive, evidence that when constant $SO_2$ concentrations are superimposed on the background of pollutants (principally $NO_x$ and $O_3$) in ambient air, or mixed with controlled amounts of $NO_x$ and/or $O_3$ in filtered chamber studies, the threshold for a yield reduction of 10% or more in long term exposures is about 130 ug/$m^3$ for the sensitive crops and trees"...

"Because the concentrations of $NO_2$ and $O_3$ are not negligible in many rural areas, more work is needed on the additive or synergistic effects of gas mixtures (particularly $SO_2$, NO, $NO_2$, and $O_3$) at near-ambient concentrations, reproducing the actual inter-gas ratios and the temporal distribution of concentration peaks for the different gases as occur in the field."....

"Theoretically, long term average concentrations of $SO_2$ between 10 and 50 ug/$m^3$ could supply the sulfur requirement of most crops in the absence of other sulfur inputs. It is not possible to specify the exact requirement from dry deposition because of the variable sulfur supply from soils, rainfall and fertilizers in different regions. However, where wet deposition exceeds 10-20 kg S/ha yr and $SO_2$ concentrations exceed 10 ug/$m^3$, addition of sulfur fertilizers to crops has not produced increases in yield. Sulfur-deficient plants may benefit from much higher $SO_2$ concentrations for short periods."

Irving, Patricia M. "Acid Precipitation Effects on Crops: A Review and Analysis of Research," Journal of Environmental Quality, Vol. 12, Number 4, October-December 1983. 442-453.

"For more than a century it has been known that vegetative growth is affected by the products of fossil fuel combustion. Recently, the acidic



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deposition phenomenon has gained increasing attention, especially when implicated as a factor responsible for economic loss. Research has been directed toward quantification of efffects; however, limitations in the design of many crop studies restricts the usefulness and applicability of the results. Acidic deposition varies in a number of ways that may affect crop yield (i.e., level of acidity, amount and intensity of rain, S and N dose). The response of these variables may be nonlinear. To allow comparisons of published acid precipitation effects research, calculations for this review were made to describe the experimental conditions, the various dose parameters, and the responses in comparable units for each investigation.

"The majority of crop species studied in the field and controlled environment experiments exhibited no effect on growth or yield as a result of simulated acidic rain. The growth and yield of some crops, however, was negatively affected by acidic rain; others exhibited a positive response. This analysis of current literature concludes that the effects of acidic precipitation on crops appear to be minimal and that when responses are observed, they may be positive or negative. More complex experimental designs and analyses may be necessary in order to examine and describe the possible subtle responses of agricultural systems to acidic precipitation."

Irving, Patricia M. "Methodology for Estimating Crop Loss from Acidic Deposition," Proceedings: Atmospheric Deposition Specialty Conference. Ed. Edward R. Frederick. Conference held Nov. 7-10, 1982, Detroit. Air Pollution Control Association, Pittsburgh, 1983. 439-453.

"Crop losses affect the production, availability and cost of food, and therefore have important economic, social, and political implication especially during this period of rapid world population growth. The fact that air-borne pollutants affect vegetative growth has been known for more than a century. Recently, the acidic deposition phenomenon has gained increasing attention, especially when implicated as a factor potentially responsible for crop yield losses. Experimental approaches utilized in traditional pollution effects research include: Field surveys, sensitivity classification, dose-response studies, and regional impact evaluation. Acid rain is a unique pollutant having special problems associated with researching its effects. For example, the description of dose for this pollutant should include rain chemistry (not just pH), rainfall rate, duration of event, total deposition, droplet size, etc. These parameters must also be considered when simulating rain in controlled studies. Due to the potential for interactions with biotic and abiotic entities, factorial research designs and multivariate analyses may be necessary for investigations of acid rain impacts on crops. Results from well planned mechanistic studies and dose-response experiments may be used to predict effects (both positive and negative), assess economic impacts, and establish tolerance thresholds for this form of pollution."



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Irving, Patricia. "Crops" section of "Effects on Vegetation" chapter, The Acidic Deposition Phenomemon and Its Effects: Critical Assessment Review Papers, Volume II, Effects Sciences. Eds. Aubrey P. Altshuller and Rick A. Linthurst. EPA Report 600/8-83-016BF, Office of Research and Development, U.S. Environmental Protection Agency, Washington, D.C., July 1984. 3-41 to 3-61.

[From the Preface to Vols. I and II: "This document is the first of several documents of increasing sophistication that assess the acidic deposition phenomenon. It will be succeeded by assessment docments in 1985, 1987, and 1989 based largely on research of the National Acid Precipitation Assessment Program. The document's original charge was to prepare 'a comprehensive document which lays out the state of our knowledge with regard to precursor emissions, pollutant transformation to acidic compounds, pollutant transport, pollutant deposition and the effects (both measured and potential) of acidic deposition.'" Volume I concerns the atmospheric sciences, while Volume II (as noted above) covers the effects sciences. More than 50 scientists contributed to the report.]

"Summary--

1) Because of limitations in research design, differences in methodologies and inconsistent results, it is difficult to compare research results directly or arrive at an overall conclusion regarding crop response to acidic deposition without a thorough description and comparison of experimental methods.

2) Complex factorial research designs and multivariate analyses may be necessary to describe adequately the relationship between acid rain dose and plant response rather than the simple univariate approach (treatment pH vs. yield) used in the past.

3) Given the above limitations to making generalizations about past research, analysis of experimental results from field and controlled-environment experiments indicates that the majority of crop species exhibited no effect on growth or yield as a result of exposure to simulated acidic rain; (acidity treatments had pH values of 4.2 or less). Growth and yield of a few crops in some studies, however, were negatively affected by acidic rain, while other crops exhibited a positive response.

4) Interpretation of available research results suggests that the net response of a crop to acidic deposition is the result of the interaction between the positive effects of sulfur and nitrogen fertilization, the negative effects of acidity, and the interaction between these factors and other environmental conditions such as soil type and presence of other pollutants. Available experimental results appear to indicate that the effects of acidic precipitation or crops are minimal and that when a response occurs it may be positive or negative. However, many crops and agricultural systems have not been adequately studied."



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Jacobson, Jay S. "Experimental Studies on the Phytotoxicity of Acidic Precipitation: The United States Experience," Effects of Acid Precipitation on Terrestrial Ecosystems. Ed. T. C. Hutchinson and M. Havas. Proceedings of the NATO Conference on Effects of Acid Precipitation on Vegetation and Soils, held in Toronto, Canada, May 21-27, 1978, Plenum Press, New York, New York, 1980. 151-160.

A rigorous method is needed--but not yet available--to predict plant response of susceptible plant species to precipitation of different compositions, occurring in precipitation events of differing characteristics, and after differing intervals without rain. A few dozen studies exist showing degress of damage to various plants from simulated acid rain, and the author reviews many of these studies. However, none of them, including the author's own work, yet formulates a sufficiently rigorous and comprehensive concept of precipitation "dose" nor of plant "response" to permit scientifically valid dose-response relationships to be prepared for acid rain and any species of vegetation.

Jacobson, Jay S. "The Influence of Rainfall Composition on the Yield and Quality of Agricultural Crops," Ecological Impacts of Acid Precipitation, Proceedings of an International Conference, Sandefjord, Norway, March 11-14, 1980. Ed. D. Drablos and A. Tollan. SNSF Project, Oslo, Norway, October 1980. 41-46.

Many factors, in addition to rainfall acidity, determine the magnitude and direction of the effects of rainfall composition on crops. At present, firm conclusions about the effects of acid rain are not possible, but four hypotheses for further testing are clearly suggested by view of the findings from numerous studies. These are the following: (1) The chemical composition of rain does affect the growth, development, yield, and quality of agricultural crops; (2) Rainfall acidity above pH4 presents low risk of adverse effects on crops, and in some circumstances chemical components in rain above pH4 may benefit crops, (3) Rainfall acidity between pH3 and pH4 may increase, decrease, or have no effect on crops depending on the crop, the cultivar, and other specific circumstances; (4) Rainfall acidity below pH3, especially when rain with this degree of acidity occurs repeatedly during the growing season, greatly increases the likelihood of harmful effects to crops and greatly decreases the likelihood of favorable effects.

Jacobson, Jay S. "Ozone and the Growth and Productivity of Agricultural Crops," Effects of Gaseous Air Pollution in Agriculture and Horticulture. Ed. M. H. Unsworth and D. P. Ormrod, Butterworth Scientific, Boston, 1982. 293-304.

"At present, ozone concentrations sufficient to produce foliar symptoms on susceptible vegetation occur in Great Britain and in at least seven European countries. In the USA, more crop plants and forest trees are injured by



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ozone than by any other pollutant...".... "Ozone and its precursors can be transported for hundreds of kilometres and they may extend over thousands of square kilometres. Ozone can persist in the atmosphere overnight in layers above the surface of the earth where there are few scavenging mechanisms. Nonurban air contains smaller amounts of compounds which react with ozone, so ozone can persist for longer periods in rural areas."....

"As recently as 1977, it was not clear whether susecptibility to foliar symptoms is correlated with yield losses... The weight of evidence now indicates that foliar-symptom production is not a reliable index of effects on plant growth or yield... Recurrent exposures to ozone over extended periods during the development of the crop are unlikely to produce close relationships between foliar symptoms and yield, except when the harvested product is the foliage."....

"[C]rop plants grown in the field often are less susceptible to yield reduction by ozone than those grown indoors. There is one important exception to this conclusion. A special combination of environmental conditions can predispose field-grown plants to injury by ozone. A period of poor growing weather with no ozone, followed by excellent growing conditions, can produce rapid gas exchange between leaves and the atmosphere and large amounts of new uninjured foliage. Under these circumstances, field-grown plants can be unusually susceptible and a coinciding period of exposure to ozone could be more injurious to fieldgrown plants that would otherwise be indicated from results obtained with indoor plants...".....

"All levels of biological organization can be affected by ozone, beginning with subcellular effects...and resulting in losses in productivity... If repair processes cannot successfully overcome these changes, than foliar symptoms develop, growth may be reduced, leaf senescence accelerated and yield decreased. When photosynthesis is impaired, the supply of metabolites is reduced. Shoots have priority in the utilization of assimilates: Consequently, inhibition of root development is one of the intial effects of ozone... Storage capacity of the plant is diminished and transport of nutrients and water to developing fruit decreases... Reproductive structures are particularly vulnerable to reduced photosynthetic capacity because they abscise prematurely in response to severe competition with other organs for limited supplies of assimilate..."

No doubt, effects of ozone on distribution of dry matter also vary with pattern and dose of ozone and environmental and cultural conditions... Significant reductions in number or mass of reproductive organs have been reported for bush beans, soybeans, tomato, and wheat... The nature and magnitude of effects of ozone on vegetation are not determined by concentration alone. Both the occurrence and severity of effects are dependent on the frequency of ozone exposures, the durations of exposure, the length of time between exposures, the magnitude of fluctuations in concentrations, the time of day of exposures, their sequence and pattern, and the total flux of ozone to the plant as it is affected by canopy characteristics and leaf boundary layers."



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Kohut, Robert J., Allen S. Heagle, Howard E. Heggestad, Lance W. Kress, and O. Clifton Taylor. "The National Crop Loss Assessment Network: A Summary of Field Studies," Proceedings of the 75th Annual Meeting of the Air Pollution Control Association at New Orleans, Louisiana, June 20-25, 1982, Paper No. 82-69.5, Air Pollution Control Association, Pittsburgh, 1982.

"A prerequisite for the assessment of the economic impacts of air pollutants on agriculture is an understanding of the relationships between pollutant exposure and crop yield. The development and analysis of these dose-response relationships is the mission of the National Crop Loss Assessment Network (NCLAN) field program. Field studies are being conducted by Boyce Thompson Institute, Ithaca, NY; North Carolina State University, Raleigh, N.C.; Beltsville Agriculture Research Center, Beltsville, MD; Argonne National Laboratory, Argonne, IL; University of California, Riverside, CA; and Lawrence Livermore Laboratory, Livermore, CA. The research sites represent a cross-section of agricultural areas of the United States and provide the opportunity to grow a variety of agriculturally important crops."

"To produce dose-response data of the greatest value, efforts were taken to insure that the crops would be grown according to common agricultural pratices, that the pollutant exposure regions would be similar to those currently being experienced or potentially occurring, and the plant response would be assessed in a manner that was associated with economic value. The exposure systems, pollutant regimes, and data analysis were made as uniform as feasible among the participant sites. Rigorous quality assurance programs for pollutant monitoring and biological measurements were applied to all studies."

The following crops have been studied for yield response to air pollutants, and, in general, dose-response relationships have been estimated: Red kidney bean, soybean, peanut, tomato, field corn, and lettuce.

Larsen, Ralph I., and Walter W. Heck. "An Air Quality Data Analysis System for Interrelating Effects, Standards, and Needed Source Reductions: Part 3. Vegetation Injury," Journal of the Air Pollution Control Association, Vol. 26, No. 4, April 1976. 325-333.

"Acute leaf injury data are analyzed for 19 plant species exposed to ozone and sulfur dioxide. The data can be depicted by a new leaf injury mathematical model with two characteristics: (1) a constant percentage of leaf surface is injured by an air pollution concentration that is inversely proportional to exposure duration, raised to an exponent; (2) for a given exposure duration, the percent leaf injury as a function of pollutant concentration tends to fit a lognormal frequency distribution. Leaf injury as a function of laboratory exposure duration is modeled and compared with ambient air pollution concentration measurements for various averaging times (1, 3 and 8 hours) to determine which exposure durations are probably most important for setting ambient air quality standards to prevent or reduce visable leaf



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injury. The 1, 3, and 8 hour threshold injury concentrations are determined for each of the 19 plant species studied. Fixed, nonoverlapping ambient air quality measurements and standards are recommended for averaging times of 1, 3, and 8 hours."

Lee, Jeffrey J. "The Effects of Acid Precipitation on Crops," Acid Precipitation--Effects on Ecological Systems. Ed. Frank M. D'Itri. Proceedings from the Conference on the Effects of Acid Precipitation on Ecological Systems, Michigan State University, East Lansing, 1982. 453-468.

"In 1979, Corvallis Environmental Research Laboratory-Oregon State University used field exposure chambers (potted plants) to conduct a study of the relative sensitivities of 28 major crops in the United States to sulfur acid rain, applied at constant concentration (pH 3.0, 3.5, 4.0, or pH 5.6 control....). Results....indicated that, within the range of ambient concentration, sulfuric acid rain can:

(1) decrease the yield of root crops such as radish, carrot, and beet by as much as 76 percent;
(2) decrease the yield (as much as 30%) and marketability of leaf crops such as spinach, Swiss chard, and mustard greens by causing severe foliar injury;
(3) cause visible injury to tomatoes;
(4) increase the yield of fruit crops such as tomato, green pepper, and strawberry (up to 72%);
(5) increase the productivity of forage crops such as alfalfa, orchard grass, and timothy (up to 31%)."

"Extreme caution should be used when considering the results of this (or any other) experiment on the effects of acid rain on plant growth.... Thus, at best, the data ....might define a potential range of effects, and might tentatively define potentially sensitive classes of crops....In a 1980 field study, we found that sulfuric-nitric acid rain (2:1 by equivalents) at pH 4.0 decreased corn yield by 9 percent (statistically significant at $p = 0.05$). Decreases at pH 3.5 and 3.0 were 4 percent and 0 percent; however, these were not statistically significant.....We found that alfalfa and grass productivities were stimulated by sulfuric acid rain in both field-exposure chamber (potted plants) and field experiments. However, in field experiments with 2:1 sulfuric-nitric (by equivalent) rain, stimulation occurred only during the early part of the growing season; total annual production was unaffected by 2:1 acid rain. Thus, response depended on the specific anions present, and not just on pH. No field experiment data are available for wheat. In a field-exposure chamber (potted plants) experiment, wheat was not significantly affected by simulated sulfuric acid rain....Interactions between acid rain and other environmental factors (such as air pollutants, water stress, soil characteristics, temperature) have scarcely been studied. Before a credible assessment of the economic impact of acid rain on crops can be done, the mechanisms of response have to be studied and the predictive capability enhanced and validated."



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Loucks, Orie L. and Thomas V. Armentano. "Estimating Crop Yield Effects from Ambient Air Pollutants in the Ohio River Valley," Journal of the Air Pollution Control Association, Vol. 32, No. 2, February 1982. 146-150.

"The apparent present effect of regional pollutant loads on crops and forests in the central midwest states was evaluated as part of the Ohio River Basin Energy Study (ORBES). The consequences of the local and regional loadings of $SO_2$ and $O_3$ for agricultural yields are summarized as "crop-loss coefficients," based on the published experimental effects data and applied to agricultural lands in the Ohio Valley region through regional monitoring of the two pollutant gases. The results are shown as upper and lower bounds containing the most probable crop loss values. The results are also reported as total potential increases in crop yields for the ORBES region, expressed as bushels, appropriate within the limits of uncertainty, for economic and related energy policy evaluations."

"Potential crop production gains from $O_3$ abatement are estimated in 1976 to have been: For soybeans, a potential gain of between 28 and 144 million bushels; for corn, a potential between 85 and 318 million bushels; and, for wheat, between 5 and 18 million bushels....[P]otential annual gain expected from $SO_2$ abatement was summarized as: For soybeans, in the range from 0.65 to 2.12 million bushels; for corn, from 0 to 3.53 million bushels; and, for wheat, from 0.21 to 0.48 million bushels. The very small size of these effects in comparison to the $O_3$ results can be attributed to the smaller acreage involved * as well as the lower loss-coefficients."

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* - Only crop acreages within defined impact zones around electric power plants were covered by $SO_2$ abatement estimates.

Miller, F. P. "Acid Rain: Something Else to Worry About," Turf Bulletin, Vol. 15 (4) 1979. 11.

The author briefly discusses the results of several acid rain studies. The agricultural impact of acid rain is both a blessing and a curse. The sulfur added through air pollution is often sufficient for sustaining crop needs, saving the farmer the expense of such additions. However, a number of studies are indicating adverse impacts of acid rain on soil pH, aluminum release, plant communities, long-term soil formation processes, and other systems. For agriculture, additional acidity can be managed by liming. Thus, acid rain is not an immediate threat to farming nor soil resources.



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National Research Council, Committee on Medical and Biologic Effects of Environmental Pollutants. Ozone and Other Photochemical Oxidants, National Academy of Sciences Publishing Office, Washington, D. C., 1977.

The Executive Summary of the report contains a sub--section on "Effects on Plants, Ecosystems, and Materials." Excerpts from this sub-section follow:

"Considerable effort has gone into controlled exposures to ozone and into field studies. Leaf stomata are the principal sites for ozone and PAN (peroxyacetylnitrate) entry into plant tissue. Closed stomata will protect plants from these oxidants. Both ozone and PAN may interfere with various oxidative reactions within plant cells. Membrane sulfhydryl groups and unsaturated lipid components may be primary targets of oxidants. Young leaf tissue is more sensitive to PAN; newly expanding and maturing tissue is most sensitive to ozone. Light is required before plant tissue will respond to PAN; that is not the case with ozone.

"Oxidants reduce yields of many plants, especially sensitive cultivars. Chronic exposures to concentrations between 0.05 and 0.15 ppm will reduce soybean, corn, and radish yields. The threshold appears to be between 0.05 and 0.1 ppm for some sensitive cultivars--well within values monitored in the eastern United States. Growth or flowering effects on carnation, geranium, radish, and pinto bean have been found at chronic exposures to ozone at 0.05-0.15 ppm....Several researchers are including pollutant stress in standard breeding programs and thus are breeding for tolerance. Interim measures involve the use of chemical sprays. Such sprays are not now economically feasible; but they are being tested, and some are protective..."

"The permanent vegetation constituting natural ecosystems receives much greater chronic exposure than the short-lived vegetation that makes up the agroecosystem subject to intermittent short-term fumigations. Each situation has measurable economic and aesthetic effects, but on different time scales. The single agricultural ecologic system (the agroecosystem) has little resilience to pollutant stress; losses are sometimes immediate and occasionally catastrophic. The natural ecosystem is initially more resistant to pollutant stress because of species diversity, but the longer chronic exposures disrupt the system. Simulation models of ecosystem components are under development. The study of such models and their interaction offers the possibility of determining the longterm effects of pollutants on natural ecosystems and agroecosystems."

Office of Technology Assessment, Congress of the United States. Acid Rain and Transported Air Pollutants: Implications for Public Policy. Report OTA-O-204, June 1984. Washington, D. C.

The principal objective of this report is to present and analyze policy options for dealing with the acid rain and air pollution issues. Much of



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the report is devoted to policy analysis. However, in a portion of the Summary, in Chapter 3, and in Appendix B extensive material dealing with effects of these pollutants is also presented, including agricultural effects.

With respect to crops, the OTA report summarizes its findings as follows: "Transported air pollutants adversely affect agricultural productivity. Up to 90 percent of the damage to crops from air pollutants may be due to ozone. Large areas of the United States, including much of the Midwestern Corn and Soybean Belts, are exposed to high levels of ozone. This study estimates that if ozone levels were reduced to their natural background levels, corn yields would have been 2 percent higher, wheat yields 5 percent higher, soybean yields 13 percent higher, and peanut yields 24 percent higher. Based on the value of these crops, ozone causes about a 6- to 7- percent loss of U.S. agricultural productivity.

"Many areas of abundant agricultural production, such as Illinois, Indiana, and Ohio, also receive high levels of acid deposition. Some experiments using simulated acid rain have demonstrated reduced yields of agricultural crops, but others have found no effect."

Reinert, R. A., A. S. Heagle, and W. W. Heck. "Plant Responses to Pollutant Combinations," Response of Plants to Air Pollution. Ed. J. B. Mudd and T. T. Kozlowski. Academic Press, Inc., New York, 1975. 159-177.

The authors attempt to identify most of the implications and known effects of pollutant combinations on plants. Plant responses to pollutants are discussed for mixtures of $SO_2$ and $O_3$, $SO_2$ and $NO_3$, $SO_2$ and hydrogen fluoride and other pollutant combinations. In addition to environmental and plant variables that affect the response of plants to single pollutants,... "[t]hree additional variables may affect plant response to pollutant combinations: (1) The concentration of each gas in the combination exposures with respect to the injury thresholds of the separate pollutants; (2) the ratio of the concentration of each gas to the other; and (3) whether the combined pollutant stress is applied simultaneously, sequentially, and/or intermittently..." In some cases, mixtures of ozone and sulfur dioxide tended to reduce foliar growth of broccoli, cabbage, radish, tomato, and tobacco as much as the additive injury from the individual pollutants. In other cases, mixtures of the same pollutants reduced the growth of these plants plus eastern White Pine, soybean, and alfalfa more than the additive injury from the individual pollutants.



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Severson, John G. "Sulfur and Higher Plants," Sulfur in the Environment. Report of the Missouri Botanical Garden, St. Louis, Missouri, April 1975. Revised July 1975. 92-111.

"Over an extended period, precipitation and/or air which contains sulfur will affect vegetation. In most cases, foliar contact with sulfur dioxide above a concentration of 0.5 ppm will retard growth by depressing metabolic processes, while the washing of excess aerial sulfur dioxide into the soil will result in a loss of buffering capacity and the leaching of essential nutrients." Depending upon the relationship between the sulfur dioxide concentration and exposure time, adverse plant responses may be placed into three general categories: Acute, chronic, and physiological and/or biochemical injury. Acute injury is usually characterized by a severe burning of the foliage in the interveinal areas and along leaf margins. In many plant species, low level exposure to sulfur dioxide results in general chlorosis. Physiological and biochemical injury to plants includes alteration of: (1) Photosynthetic rates; (2) diffusion resistance of gases through stomata; and (3) enzymic activity, and nitrogen metabolism.

Shurtleff, Malcolm C., M. B. Linn, and James B. Sinclair. "Plant Damage from Air Pollution," Plant Diseases, Bulletin No. 1005 (Revised), Department of Plant Pathology, University of Illinois, Urbana-Champaign.

This bulletin, written for a general readership, lists many agricultural plants of commercial value which are sensitive (or resistant) to the following pollutants: Sulfur dioxide, fluorides, chlorine, ozone, peroxyacetylnitrate (PAN), and ethylene. The Bulletin lists several professional publications as its information source. The Bulletin concludes, on the basis of literature review, that ozone is the most significant plant-toxic air pollutant in the U.S., followed by PAN. Effects of pollutant combinations are not discussed.

Skelly, John M., Milton F. George, Howard Heggestad and Donald T. Krizek. "Air Pollution and Radiation Stresses," Modification of the Aerial Environment of Plants. Ed. B. J. Barfield and J. F. Gerber. ASAE Monograph published by American Society of Agricultural Engineers, St. Joseph, Michigan, 1979.

The authors discuss recent research pertaining to air pollution as an agent causing plant stress. Their conclusion is that the major air pollutants causing plant stress injury and economic losses are photochemical oxidants (primarily ozone), sulfur dioxide, fluorides, and nitrogen dioxide. Other pollutants of concern are peroxyacetylnitrate (PAN), ethylene, chlorides, acid rain, and various particulates. Plants grown in humid areas are more susceptible to ozone and sulfur dioxide than plants grown in arid areas. Species and varieties within species vary significantly in their tolerance to air pollutants, a characteristic frequently used in minimizing air pollution losses.



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Tabatabai, M. A., R. E. Burwell, B. G. Ellis, D. R. Keeney, T. J. Logan, D. W. Nelson, R. A. Olson, G. W. Randall, D. R. Timmons, E. S. Verry, and E. M. White. Nutrient Concentrations and Accumulations in Precipitation Over the North Central Region, North Central Regional Research Publication No. 282, sponsored by Agricultural Experiment Stations of Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, Wisconsin and the U.S. Department of Agriculture, cooperating. Published as Research Bulletin 594 by the Agriculture Experiment Station, Iowa State University, Ames, Iowa, November 1981.

"The chemical composition of precipitation and its effect on soils, vegetation, and aquatic life have received considerable attention in recent years. This report was prepared to pool the information available in the states of the North Central Region on nutrient concentrations and accumulations by precipitation. In addition, comparison was made of emission of particulates, $SO_x$, $NO_x$, CO, and hydrocarbons from various sources in each state in the study region.

Results showed that, although emission of $SO_x$, $NO_x$, and particulates varies greatly among the states, the greater emissions are in Ohio and the least in North Dakota and South Dakota. Nitrogen ($NH_4^+$ and $NO_3^-$), sulfur ($SO_4^{2-}$), and phosphorus ($PO_4^{3-}$), concentrations and accumulations by precipitation in these states are very similar. Generally, the annual inorganic N deposition ranged from 5 to 20kg/ha. Of these amounts, 50% was in the $NH_4^+$ form and the other 50% in the $NO_3^-$ form in Iowa, but generally more $NH_4$-N than NO3-N is deposited in this region.

The concentration of $SO_4$-S varied among the sites and seemed to be high during fall and winter and low during the spring and summer. The annual deposition of S ranged from 5 to 15 kg/ha per year. The soluble $PO_4$-P concentrations were very low; they ranged from 0 to 120 ug/l. The annual deposition of P was insignificant compared with that present in soils and added in fertilizers; it ranged from <0.1 to 1 kg/ha.

Insufficient data are available on pH of precipitation in this region, but the limited information indicates that pH of precipitation is slightly alkaline (pH = 6) in Iowa, Nebraska, and one site (Lamberton) in Minnesota and slightly acid (pH, 4 to 5) in Illinois, Michigan, one site (Marcell) in Minnesota, and Ohio compared with that expected (pH = 5.7) for precipitation in equilibrium with normal $CO_2$ in the atmosphere.

It is concluded that current levels of N, S, and P (especially S) in precipitation in the region are beneficial to agricultural production. This is especially true for agricultural and grassland ecosystems that receive little or no fertilizers."



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Taylor, O. C., C. R. Thompson, D. T. Tingey, and R. A. Reinert. "Oxides of Nitrogen," Responses of Plants to Air Pollution. Ed. J. B. Mudd and T. T. Kozlowski. Academic Press, New York, 1975. 121-139.

Of the oxides of nitrogen, the most important air pollutants are nitric oxide (NO) and nitrogen dioxide ($NO_2$).

"Several factors, such as concentration of pollutant, length of exposure, species of plant, stage of plant development, plant environment (temperature, light, humidity, soil moisture, mineral nutrition), and resistance of species (variety or clone), influence the degree of injury suffered by vegetation from air pollutants."

More than 25 researchers have conducted fumigation experiments on plants (crops, ornamentals, trees) to determine the extent to which these plants are injured by various exposure levels of nitrogen oxides. Among plants ranked as most susceptible to injury by $NO_2$ are: Peas, alfalfa, clover, carrots, lettuce, tobacco, oats, parsley, and barley. Among those ranked moderately susceptible are: Rye, celery, corn, wheat, tomato, potato, and strawberry.

The authors use data from these fumigation experiments to derive a functional relationship between length of plant exposure to $NO_2$ (in days) and $NO_2$ concentration (in parts per million). The resulting function describes a frontier zone of "acceptable levels" of $NO_2$, above which injury to many plants tends to occur, but below which it does not. Thus, prolonged exposure at low concentrations (above the frontier zone) can produce plant injury as well as brief exposure at high concentrations (also above the frontier zone).

Although the experiments have probed the concentrations and exposure values at which injury can occur, in general, ambient concentrations of $NO_2$ around the United States are not high enough (not above the frontier zone) for acute plant damage symptoms to occur. Nevertheless, subtle or invisible plant damage can occur at pollutant doses not sufficiently high to cause visible damage. [Included in types of subtle damage is reduction in plant seed or fruit yields, which may be economically important.]

Treshow, Michael. "Interaction of Air Pollutants and Plant Diseases," Responses of Plants to Air Pollution. Ed. J. B. Mudd and T. T. Kozlowski. Academic Press, Inc., New York, 1975. 307-334.

"Studies of air pollutant-disease interaction are few. The limited field observations and research only indicate what might happen in the case of a few diseases and pollutants....Realistically, the only probable pollutant-disease interaction is where the pollutant physically injures the host tissue to where significant infection courts are provided. The physiological changes induced by pollutants that might influence disease development



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occur only at rather prolonged exposures to pollutant concentrations.... and then....only on the most pollutant-sensitive plant species."

"Secondary effects of pollutants such as $SO_2$ through their impact on the soil and soil flora might be more significant."....Laboratory studies indicate that...."[i]n the long run, air pollutants might conceivably influence plant diseases to such a degree as to alter the species composition and density in the plant community."

Tukey, H. B., Jr. "Some Effects of Rain and Mist on Plants, With Implications for Acid Precipitation," Effects of Acid Precipitation on Terrestrial Ecosystems. Ed. T. C. Hutchinson and M. Havas. Proceedings of the NATO Conference on Effects of Acid Precipitation on Vegetation and Soils, held in Toronto, Canada, May 21-27, 1978, Plenum Press, New York, 1980. 141-150.

One of the major effects of rain and mist on plants is the leaching of nutrients from plant parts and the deposition of these nutrients upon the soil surrounding the plants, where the nutrients may be promptly recycled to the plant by root absorption. Acidity in precipitation may modify this natural process, and these potential modifications need to be studied much more thoroughly. For example, acidity may severely damage (by leaching) a plant's protective cuticle layer, leaving a plant more vulnerable to disease.

U. S. Environmental Protection Agency, Office of Air and Waste Management. "Diagnosing Vegetation Injury Caused by Air Pollution." Prepared by Applied Science Associates, Inc., Valencia, Pennsylvania. EPA Report 450/3-78-005, U. S. Environmental Protection Agency, Research Triangle Park, North Carolina, February 1978.

This is a handbook designed primarily to assist field inspectors in the collection of data to be used in assessing crop damage and economic loss caused by air pollutants. Plant parts and functions which may be injured by air pollutants are outlined. Pollutant sources, atmospheric chemistry, monitoring data, symptomatology, factors affecting plant response, injury threshold doses, air quality standards and relative sensitivity of plants to various air pollutants are discussed. Diagnosis of suspected air pollution injury to vegetation is outlined.



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Individual Studies

Amundson, R. G. and L. H. Weinstein. "Joint Action of Sulfur Dioxide and Nitrogen Dioxide on Foliar Injury and Stomatal Behavior in Soybean," Journal of Environmental Quality, Vol. 10, No. 2, 1981. 204-205.

"Six cultivars of soybeans were screened for susceptibility with respect to foliar necrosis after exposure to short-term, relatively high concentrations of $SO_2$ or $SO_2$ in combination with $NO_2$. In all screening trials, the combination of $SO_2$ and $NO_2$ produced less foliar injury than did the same concentration of $SO_2$ alone... Leaf resistance measurements were made on the upper and lower leaf surfaces of the eighth and ninth trifoliates on two of the six plants per cultivar exposed to each treatment. Leaf resistances increased somewhat during exposure to $SO_2$, but they increased dramatically in plants exposed to the combination of $SO_2$ and $NO_2$. The antagonistic effects of $SO_2$ and $NO_2$ on the development of necrotic lesions reported can be explained, at least partially, by pollutant avoidance due to stomatal closure caused by the combination of the two pollutants."

Ashenden, T. W. and T. A. Mansfield. "Extreme Pollution Sensitivity of Grasses When $SO_2$ and $NO_2$ are Present in the Atmosphere Together," Nature, Vol. 273, 11 May 1978. 142-143.

"Predictions of the possible effects of atmospheric pollution in vegetation have usually been based on the results of experiments in which plants were fumigated in the laboratory."...."We found that laboratory experiments can underestimate the amount of injury resulting in the field, and report here that combinations of $SO_2$ with $NO_2$ give more realistic effects."...."We have now carried out some preliminary studies, the results of which suggest that the combined effects of these two gases could be the cause of serious losses in crop production in polluted areas, and that when $SO_2$ interacts with $NO_2$ there is a large increase in the toxicity to plants."

Four common pasture grasses were studied: Cocksfoot, Italian ryegrass, Timothy and Smoothstalked meadowgrass. "Treatment with combined $SO_2$ and $NO_2$, however, caused large statistically significant reductions in total dry weight, associated with reductions in leaf area, in all four species. With the exception of Italian ryegrass, the reductions were greater than 75%."...."The relative sensitivities of the four grasses were surprisingly different. Although timothy exhibited the greatest reduction in dry weight when exposed to $SO_2$, it was one of the species not significantly affected by $NO_2$. With such marked differences in response to the three treatments, we suggest that in a mixed sward in the field, different mixtures of $SO_2$ and $NO_2$ could result in quite different changes in species composition."



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Bennett, Jesse H. and A. Clyde Hill. "Inhibition of Apparent Photosynthesis by Air Pollutants," Journal of Environmental Quality, Vol. 2, No. 4, 1973. 526-529.

"The reversible effects of hydrogen fluoride, sulfur dioxide, and chlorine exposures on net carbon dioxide absorption rates (apparent photosynthesis) of alfalfa and barley plants were studied. Pollutant exposures required to reversibly depress $CO_2$ uptake rates and to cause cellular necrosis in the leaves were appraised. Plant responses to these air pollutants were compared to responses observed from previous equivalent studies with ozone, nitric oxide, and nitrogen dioxide. The experimental data show that $CO_2$ uptake could be reversibly suppressed by exposure dosages of these pollutants which did not cause cellular destruction in the leaves. However, except for the nitrogen oxides, some necrosis resulted from treatments which depressed $CO_2$ uptake rates more than 25-60 percent. The six air pollutants can be ranked in the following order, from highest to lowest, according to the relative amounts that plant $CO_2$ uptake rates were depressed by the end of two hours of pollutant exposure: HF, $O_3$, $Cl_2$, $SO_2$, $NO_2$, NO. The phytotoxicants ranked in essentially the reverse order when compared on the basis of the rapidity that $CO_2$ uptake was suppressed as a function of exposure time."

Butler, L. Knudson, and T. W. Tibbits. "Stomatal Mechanisms Determining Genetic Resistance to Ozone in Phaselous vulgaris L. (Bean)," Journal of the American Society of Horticultural Science, Vol. 104, No. 2, 1979. 213-216.

"The ozone-sensitive bean cultivars 'Spurt' and 'Blue Lake Stringless' and the ozone-resistant cultivars 'Black Turtle Soup' and 'French's Horticultural' were grown from seed in a growth chamber. The resistant cultivars had 25 percent fewer stomata per square millimeter of leaf area than the sensitive cultivars and exhibited partial stomatal closure following exposure to 134 pphm ozone for 1 hour, while the sensitive cultivars did not. Stomatal closure was determined to be more important than reduced stomatal frequency in providing resistance to ozone. On the basis of previously established ozone dose-response data for P. vulgaris, the stomatal mechanisms appeared to account for the difference in ozone sensitivity between the sensitive and resistant cultivars. Neither leaf area nor leaf expansion rate were correlated with genetic resistance to ozone in these cultivars."

Cameron, J. W. and O. C. Taylor. "Injury to Sweet Corn Inbreds and Hybrids by Air Pollutants in the Field and by Ozone Treatments in the Greenhouse," Journal of Environmental Quality, Vol. 2, No. 3, 1973. 387-389.

"Five inbreds of Zea mays L. and three of their $F_1$ hybrids were grown in the field under natural summer air pollution conditions. Four of the



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inbreds and two hybrids were grown in greenhouses and received controlled ozone treatments. The cultivars showed highly significant differences in injury under field conditions, but much smaller differences in greenhouse tests. In the field, four inbreds were relatively resistant; the fifth was highly susceptible. The three hybrids showed some correlation with the resistance of their parents. In the greenhouse, with repeated dosages of ozone, all tested inbreds showed substantial damage when 4 to 7 weeks old, but at flowering the field-susceptible inbred was most severely damaged. The hybrids also showed severe damage as young plants, while at flowering their damage from greenhouse treatments was related to their field susceptibility. Injury symptoms in the field were typical of the ozone injury in the greenhouse. In all cultivars, young leaves were less injured than fully mature leaves."

Clarke, B. B., M. R. Henninger and E. Brennon. "An Assessment of Potato Losses Caused by Oxidant Air Pollution in New Jersey," Phytopathology, Vol. 73, No. 1, January 1983. 104-108.

"During 1978 and 1980, three potato cultivars were grown in the field and harvested according to standard commercial practices. A drench of EDU, (N-[2-(2 oxo-1-imidazolidinyl) ethyl] N' - phenylurea), an antioxidant, was applied to one-half of the plants to protect against oxidant injury. The order of foliar sensitivity of these cultivars to oxidant was: Norland; Norchip; Green Mountain. Generally, foliar injury was a function of the cumulative oxidant dose, and the time of maximum plant susceptibility was cultivar dependent. When over 60% of the foliage was injured, tuber yield was reduced 25 and 31% in plants of cultivars Norland and Norchip, respectively. Yield reduction was traced to smaller sized potatoes in the Norland cultivar and to fewer tubers in the Norchip cultivar. The specific gravity of Norland tubers was significantly reduced in both years. When the two cultivars showed equally severe foliar injury, tuber yield of Norchip showed a greater reduction than Norland."

Evans, Lance S. "Foliar Responses that May Determine Plant Injury By Simulated Acid Rain," Polluted Rain. Ed. T. Y. Toribara, M. W. Miller and P. E. Morrow. Proceedings of the Twelfth Rochester International Conference on Environmental Toxicity, University of Rochester, Rochester, New York. May 21-23, 1979. Plenum Press, New York, 1980. 239-257.

"Experiments were performed to categorize the responses of foliage of several plant species after exposure to simulated acid rain in order to predict the relative sensitivities of plants to acid precipitation in nature. The investigations were performed to...[help] diagnose acid rain injury...[F]oliage of pinto bean, soybeans, and sunflower were most sensitive to simulated acid rain among the species tested." Sensitivity was measured



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by percentage of leaf area showing lesions after exposure to rain acidity ranging from pH 3.4 (1 percent of leaf area with lesions, soybeans); at pH 2.7, about 6 percent of the leaf area showed lesions, pinto bean and soybeans. Sunflower was less sensitive at pH 2.7. However, at pH 2.3 both pinto bean and sunflower showed 10 percent of their leaf area with lesions. Soybeans were not tested at a pH less than 2.7.

Evans, Lance S., Christine A. Conway, and Keith F. Lewin. "Yield Responses of Field-Grown Soybeans Exposed to Simulated Acid Rain," Ecological Impacts of Acid Precipitation, Proceedings of an International Conference, Sandefjord, Norway, March 11-14, 1980. Ed. D. Drablos and A. Tollan, SNSF Project, Oslo, Norway, October 1980. 162-163.

Soybean plants (variety Amsoy 71) showed and increasingly adverse yield response to greater and greater degrees of acidity in simulated acid rain applied during the 1979 growing season. Those plots exposed to greater degrees of acidity over the season had fewer pods per plant, and thus a smaller total number and mass of seeds.

Evans, L. S. and T. M. Curry. "Differential Responses of Plant Foliage to Simulated Acid Rain," American Journal of Botany, Vol. 66, No. 8, September 1979. 953-962.

Experiments estimated the relative sensitivities of foliage of soybean, spiderwort, pin oak, and bracken fern to acid rain and to identified leaf surface and anatomical changes attributable to simulated acid rain. Such changes can help to assess acid rain injury. Using greenhouse plants and artificial acid rain, the four plant species were exposed to simulated rain of different acidities, ranging from pH 5.7 to pH 2.3. At pH 2.5, foliage of bracken fern was most sensitive, pin oak the least, with soybean and spiderwort both intermediate in sensitivity. After 6 20-minute daily exposures to simulated rain of pH 2.7, soybean foliage showed lesions on about 7 percent of the leaf surface. However, younger leaves were more sensitive than older leaves. Older leaves were not only less sensitive, but as the total leaf area expanded, the percentage of area afflicted with lesions tended to decrease. Possible effects on soybean yields were not studied by the experiment.



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Evans, Lance S., Nicholas F. Gmur, and Filomena Da Costa. "Leaf Surface and Histological Perturbations of Leaves of Phaseolus Vulgaris and Helianthus Annuus After Exposure to Simulated Acid Rain," American Journal of Botany, Vol. 64, No. 7, August 1977. 903-913.

Experiments were performed to determine the response of Phaseolus vulgaris (bean) and Helianthus annuus (sunflower) leaves after exposure to several daily events of simulated sulfate acid rain ranging from pH 5.7 to 2.3. Leaf injury began at pH 3.1 and became more severe with rain of greater acidity. "Initial injury to adaxial leaf surfaces occured near trichomes and stomata....Lesion frequency was not correlated with density of either stomata or trichomes but was correlated with degree of leaf expansion. The number of lesions per unit area increased with total leaf area.... Lesion development on Phaseolus vulgaris followed a specific course of events after exposure to simulated rain of known composition, application rate, drop size frequency, drop velocities, and frequency of exposures. These results allow development of further experiments to observe accurately other parameters, such as nutrient inputs and nutrient leaching from foliage, after exposure to simulated acid rain."

Evans, Lance S., and Land and Freshwater Environmental Sciences Group. "Effects of Acidity in Precipitation on Terrestrial Vegetation," Water, Air and Soil Pollution, Vol. 18, Nos. 1/2/3, July/August/October 1982. 395-403.

"Present experimental results suggest that acidic precipitation would initially affect organisms on leaf surfaces and epidermal cells of leaves of higher plants. Differences in responses of plant foliage among plant species to acidic precipitation appear to be due to the degree of leaf wetting and differences in responses of leaf cells to low pH rain....In one experiment, at Brookhaven National Laboratory, field grown soybeans were exposed to short duration rainfalls of either pH 4.0, 3.1, 2.7, or 2.3 to provide inputs of 50,397,998 or 2506 ueq of hydrogen ions, respectively, above ambient levels throughout the growing season. These additional hydrogen ions decreased seed yield, 2.6, 6.5, 11.4, and 9.5%, respectively." The authors believe that researchers must design additional experiments with adequate experimental controls to assess the impact of acidic rain if the acidity should increase.

Evans, Lance S., and Keith F. Lewin. "Growth, Development and Yield Responses of Pinto Beans and Soybeans to Hydrogen Ion Concentrations of Simulated Acidic Rain," Environmental and Experimental Botany, Vol. 21, No. 1, February 1981. 103-113.

"Greenhouse experiments were performed to detemine changes in seed yield of soybeans (Glycine max L.) and pinto beans (Phaseolus vulgaris L.) exposed



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to simulated acid rain of pH 5.7, 3.1, 2.9, 2.7, and 2.5. Simulated rain of pH 3.1 and above decreased the dry mass of seeds, leaves, and stems on pinto beans compared with plants exposed to rain of pH 5.7. The decrease in seed yield was comparable to reduction in biomass of leaves and stems. The decrease in yield of pinto beans by simulated acidic rain was attributed to a decrease in the number of seeds per pod. In soybeans, simulated acidic rain of pH 3.1 and 2.5 decreased the dry mass of both stems and leaves. An increase in seed yield occurred when plants were exposed to rain of pH 3.1 which resulted from a larger dry mass per seed. Simulated acidic rain decreased leaf enlargement of the first-produced leaves of pinto beans but had no effect on enlargement of leaves produced later in development. In soybeans, a decrease in leaf enlargement occurred in leaves produced later in development than in first-produced leaves. Rain acidity response functions were established to better understand (1) the sensitvity of various processes of simulated acidic rain; and (2) how the differences in sensitivity of these various processes affect plant productivity."

Evans, L. S., K. F. Lewin, and M. J. Patti. "Effects of Simulated Acidic Rain on Yields of Field-Grown Soybeans," The New Phytologist, Vol. 96, No. 2, February 1984. 207-213.

"An experiment was performed during the summer of 1982 to determine the effects of simulated acidic rain on seed yields on two commercial cultivars of soybeans from all ambient rainfalls automatically by two moveable exclusion covers and exposed to simulated rainfalls in quantities equal to the average amount of rainfall that occurs at the site. Seed yields of cultivar Amsoy exosed twice weekly to simulated rain of pH 4.1, 3.3, and 2.7 were, respectively, 3.0, 9.0, and 12.8% below yields of plants exposed to simulated rain of pH 5.6...For cultivar Williams, seed yields of plants exposed to simulated rainfalls of pH 5.6, 4.1, 3.3, and 2.7 were 11.5, 10.5, 11.4, and 11.4 grams, respectively...Plants of Amsoy and Williams grown in plots adjacent to the exclusion shelters had mean seed yields of 11.4 and 9.8 grams per plant because the number of seeds per pod did not vary among treatments for each cultivar."

Evans, Lance S., Keith F. Lewin, Mitchell J. Patti, and Elizabeth A. Cunningham. "Productivity of Field-Grown Soybeans Exposed to Simulated Acidic Rain," New Phytologist, April 1983. 377-388.

"Shielded crop experiment--Plants shielded from ambient rainfalls and exposed to simulated rainfalls of pH 4.1, 3.3, and 2.7 exhibited yields 10.6, 16.8, and 23.9%, respectively, below yields of plants exposed to simulated rainfalls of pH 5.6....The decrease in seed mass per plant with an increase in rainfall acidity resulted from a decrease in number of pods per plant, since the number of seeds per pod and the mass of individual seeds did not vary significantly among the experimental treatments."



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"Short-duration exposure experiment--....[P]lants were exposed to short-duration simulated rainfalls in addition to ambient rainfalls....Plants exposed to simulated rain of pH 4.1, 3.3, and 2.7 exhibited yield reductions of 2.7, 7.0, and 7.6, respectively, below yields of plants exposed to simulated rain of pH 5.6. As in the (shielded crop) experiment, these reductions were due to a reduction in pods per plant, since the number of seeds per pod and the mass of individual seeds did not vary significantly among the treatments."....

"Throughout the soybean growing season of 1981, ambient rainfalls supplied 1.80 kg N and 2.73 kg S per hectare. In the soybean ambient rainfall exclusion experiment described above, [shielded crop experiment] a total of 18.1 kg N per hectare as nitrate and 102 kg S per hectare as sulfate was applied in simulated rainfalls at pH 2.7. These large amounts of nitrate and sulfate did not counteract the negative effects of rainfall acidity on soybean yields."

Ferenbaugh, Roger W. "Effects of Simulated Acid Rain on Phaseolus Vulgaris L.," American Journal of Botany, Vol. 63, No. 3, March 1976. 283-288.

"Experiments were performed to determine the effects of simulated acid rain on Phaseolus vulgaris L. (kidney bean). At pH values below 3, plants exhibited a failure to attain normal height, had necrotic and wrinkled leaves, excessive and adventitious budding and premature abscission of primary leaves. Histologically, leaves had smaller cells, less intercellular space, and smaller starch granules within the chloroplasts. Respiration rates of the treated plants increased only slightly at low pH values. Apparent rates of photosynthesis increased dramatically. Both carbohydrate production and root biomass were reduced by low pH treatments, and application of Congo red indicator to the acid-treated leaf tissue showed that the cell contents were acidified to a pH below 4.0....Since acid rain does appear to result from chemical reactions of air pollutants in the atmosphere, the possibility of a resultant decrease in plant productivity is a factor which should be considered whenever expansion of electrical generating facilities or industrial complexes is considered."

Flagler, R. B. and V. B. Youngner. "Ozone and Sulfur Dioxide Effects on Three Tall Fescue Cultivars," Journal of Environmental Quality, Vol. 11, No. 3, 1982. 413-416.

In an examination to determine air pollution effects in terms of marketable yield, three cultivars of tall fescue (Alta, Fawn, and Kentucky 31) were exposed to different levels of ozone ($O_3$) and sulfur dioxide ($SO_2$), once a week, for 7 and 9 weeks, respectively. Three variables were analyzed statistically: Top dry weight (yield), tiller number, and weight per tiller. Ozone had a significant effect on all three variables. Signif-



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icant linear decreases in yield and weight per tiller occurred with increasing $O_3$ concentrations. Linear regression of these variables on $O_3$ concentration produced significantly different regression coefficients. The coefficient for Kentucky 31 was significantly greater than for Alta or Fawn, indicating that Kentucky 31 was more susceptible to $O_3$ than either of the other cultivars. Percent reductions in dry weight for the three cultivars at the highest $O_3$ level ranged from 35-53 percent. Tiller number was generally increased by $O_3$, but this variable was not useful for determining differential susceptibility to the pollutant. Sulfur dioxide treatments alone produced no significant effects on any of the variables analyzed. "Weight per tiller was unaffected by $SO_2$. Number of tillers was significantly reduced by interaction of the two pollutants. Neither $O_3$ nor $SO_2$ had an effect singly, but at the high $O_3$ level, the addition of $SO_3$ caused an 18.6 percent reduction in number of tillers. This was the only significant pollution interaction noted."

Foster, K. W., H. Timm, C. K. Labanauskas, and R. J. Oshima. "Effects of Ozone and Sulfur Dioxide on Tuber Yield and Quality of Potatoes," Journal of Environmental Quality, Vol. 12, No. 1, January-March 1983. 75-80.

"Air pollution injury of the potato plant (Solanum tuberosum L.) has been documented previously, but potato yield losses have not been estimated in replicated experiments having controlled exposures to ozone and sulfur dioxide. A controlled-environment study involving the speckle-leaf-sensitive cultivar 'Centennial Russet' was conducted to examine effects of chronic exposure to ozone and sulfur dioxide on plant growth and tuber yield and quality..."

"Plants grown outside of chambers in ambient air showed effects consistent with results obtained within the chambers. The plants grown outside... producted 58% less tuber yield than filtered air control plants."

"The yield response observed in this study suggests that ozone reduced tuber number per plant and that sulfur dioxide reduced mean tuber size. This apparent distinction may be due to the dissimilar seasonal dose patterns of the two pollutants. Ozone concentrations were initially high, relative to sulfur dioxide concentrations, but declined steadily during the growing season. Tuber production may be divided roughly into two sequential stages, which are initiation and growth. As plants matured from tuber initiation through stages of tuber enlargement, they were exposed to changing concentrations of pollutants. High ozone concentrations early in growth influenced tuber initiation significantly, but those tubers that were initiated grew to the same mean weight as tubers on untreated plants; sulfur dioxide concentration remained high throughout tuber enlargement. Although sulfur dioxide effects observed were small, the reduction in mean tuber size of sulfur dioxide-exposed plants is consistent with these pollutant and tuber growth patterns. Time of year may influence injury by ozone. Both spring and fall-planted potato crops are grown in the San Joaquin



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Valley. The spring and fall crops would be exposed to very different ozone exposure, because ozone concentrations peak in midsummer in this region. Thus, a spring-planted crop encounters increasing ozone concen trations during growth, whereas the reverse is true for a fall-planted crop. Thus, the same overall ozone exposure may affect tuber size and number differently, depending on the season of growth."

Gish, T. J., H. E. Heggestad, J. H. Bennett, and L. W. Douglas. "Effects of Ozone, Sulfur Dioxide, and Soil Moisture Stress on Soybean Yields." Manuscript submitted to Agronomy Journal for possible publication.

"The purpose of this investigation was to determine whether the interactive effects of ozone, sulfur dioxide, and soil moisture stress on soybean yields occur under controlled field conditions. In order to accomplish this task, thirty open-top chambers were placed in the field where two soybean cultivars, Forrest and Williams, were being grown. Forrest, a group 5 maturing variety, is the third most popular cultivar in the United States. Williams, a group 3 maturing variety, is the most important cultivar in the U. S...."

"Although the effects of sulfur dioxide and soil moisture on yields were significant, the impact of ozone was the most dramatic....However, there was no significant synergistic interaction between ozone and sulfur dioxide. As a consequence, averaging the effects of ozone across sulfur dioxide and vice versa is justified."

"The relationships between ozone exposure and yields for the two cultivars in the wet and dry plots are given....Generally, the trends are similar. For example, no significant differences between the charcoal-filtered and the nonfiltered treatments were evident for the moist plots with no added ozone. As the concentration of ozone was increased, however, the yields steadily decreased. For the dry plots, a significant reduction in yields (30 percent) occurred when exposed to even ambient concentrations. Unlike the wet chambers, further increases in ozone caused little additional yield losses."

"The effect of sulfur dioxide on yields was less dramatic than that of ozone. For instance, there is no significant reduction in the yields due to an .03 ppm addition of sulfur dioxide. However, there was a significant decrease in yields when the sulfur dioxide concentration was maintained at approxi- mately .10 ppm. At this latter concentration, a yield reduction of 12.4 and 13 percent was observed under the dry and wet plots, respectively..."

"This study demonstrates that there is a dramatic decrease in soybean yields when both moisture stress and ozone are present. However, eliminating moisture stress enabled the plants to tolerate the average ambient concentrations of ozone experienced in this investigation (0.047) ppm, 7-hr



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mean). Under moist conditions, there is a linear decrease in yields with increasing concentrations of ozone; however, under dry conditions, an increase in ozone levels over that in ambient air shows only a slight decrease in yields."

[An analysis of variance indicated that the effects of sulfur dioxide and ozone on yields were additive. However, the effect of moisture stress and ambient ozone (0.047 ppm) decreased yield synergistically.]

Heagle, Allen S. "Ranking of Soybean Cultivars for Resistance to Ozone Using Different Ozone Doses and Response Measures," Environmental Pollution, Vol. 19, No. 1, May 1979. 1-10.

"The relative resistance (ranking) of soybean Glycine max (L.) Merr. cultivars Dare, Hood, Lee 68 and Scott to ozone ($O_3$) was affected by the $O_3$ concentration, duration of exposure, and the response measure selected as the criterion for ranking. The ranking of cultivars obtained by exposure to chronic doses of $O_3$ was often different from that obtained from those based on foliar injury. Rankings based on primary leaf injury sometimes differed from those based on trifoliate leaf injury. The results show a need for further work in order to develop methods of screening cultivars for resistance to $O_3$."...

"This study did not identify a protocol that best predicts relative resistance of soybeans to effects on yield from $O_3$. It is not known whether acute exposures are a better indicator than chronic exposures or whether growth response is a better indicator than injury response. Except for this report and that by Tingey et al. (1973) on Dare and Hood, we know of none that considers the relative sensitivity of soybean cultivars to chronic $O_3$ exposure or growth effects as a measure of relative sensitivity. The best screening protocol may depend partially on the type of pollution stress prevalent where soybeans are grown. In areas of the United States where soybeans are grown, oxidant pollution doses are usually chronic and occur more or less consistently at concentrations between 0.05 and 0.15 ppm during the day throughout the summer. Thus, a chronic type of screening programme may be better than an acute type for predicting field resistance of soybeans to oxidants. Sulphur dioxide, however, often occurs in acute doses and a screening programme utilizing acute exposures to $SO_2$ is suggested. Field studies are needed to verify whether cultivar rankings reported here or elsewhere in the literature relate to economic effects under field conditions."

"At present the best method of determining the relative tolerance of seed or fruit crop cultivars is through measurement of yield effects under field conditions. Investigations of how experimental variables affect ranking in greenhouse studies, coupled with correlations between greenhouse and field rankings, are needed before an acceptable greenhouse screening programme can be developed."



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Heagle, Allen S., Denis S. Body, and Grady E. Neely. "Injury and Yield Responses of Soybean to Chronic Doses of Ozone and Sulfur Dioxide in the Field," Phytopathology, Vol. 64, No. 1, January 1974. 132-135.

"Beginning 14 days after emergence, soybean plants were covered by chambers and exposed for 6 h per day to ozone ($O_3$), sulfur dioxide ($SO_2$),and a mixture of these gases. Chamber treatments were carbon filtered air, 5 pphm $O_3$ (low $O_3$), 10 pphm $O_3$ (high $O_3$), 10 pphm $SO_2$, and 10 pphm $O_3$ + 10 pphm $SO_2$. Plants were also grown outside in ambient air. Injury, growth and yield of plants were evaluated 43, 92, and 133 days after exposures began. $SO_2$ alone or in the mixture did not significantly affect these responses. Low $O_3$ caused injury and defoliation but did not significantly reduce growth or yield. High $O_3$ and the mixture of $SO_2$ and $O_3$ caused injury and defoliation and reduced growth and yield. Injury was usually somewhat greater and yield somewhat less in the mixture than in high $O_3$, but these differences were not significant. The results show that soybean can sustain some ozone injury without loss of yield and unless acute episodes occur which cause extensive foliar injury, soybean yield will not be reduced in areas with seasonal daily 6-h averages of less than 5 pphm $O_3$ or 10 pphm $SO_2$."

Heagle, Allen S., Denis E. Body, and Evelyn K. Pounds. "Effect of Ozone on Yield of Sweet Corn," Phytopathology, Vol. 62, No. 7, July 1972. 683-687.

"Sweet corn, Zea mays L. Golden Midget and White Midget, were exposed to 0, 5, or 10 pphm ozone for 6 hr/day, from emergence to harvest, in field exposure chambers. Golden Midget was more sensitive to ozone than White Midget as indicated by the amount of visible injury and by reduction in growth and yield. Fresh weight of ears, number of kernels, and dry weight of kernels on plants receiving 10 pphm ozone were significantly reduced with respect to the controls in Golden Midget but not White Midget." The data from this experiment support the evidence of others who have also indicated yield loss in corn due to oxidant air pollutants. If the values obtained in this and previous research are valid under completely natural growing conditions, the yield loss in sensitive corn varieties grown in polluted areas may be greater than previously believed.

Heagle, A. S. and W. W. Heck. "Field Methods to Assess Crop Losses Due to Oxidant Air Pollutants," Proceedings of the E. C. Stakman Commemorative Symposium: Assessment of Losses Which Constrain Production and Crop Improvement in Agriculture and Forestry, Miscellaneous Publication No. 7, Agricultural Experiment Station, University of Minnesota, St. Paul, 1980. 296-305.

"The wide range of estimates for annual crop losses caused by air pollution ($135-900 million) indicates a lack of objective information on the subject. Estimates have been primarily on the presence of foliar symptoms but little



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is known on the relationships between foliar symptoms, plant growth stage, and yield loss. For the most part, previous estimates disregard subtle injury or yield loss in the absence of symptoms. Sound experimental evidence on the yield responses of plants to ambient levels of pollutants is needed before rational decisions on air pollution control strategies can be made. Recent efforts to experimentally quantify the effects of pollutants on plants in the field have centered on the use of ambient pollutant gradients, open-air exposures, protective chemicals, sensitive and resistant cultivars, or field exposure chambers."

Heagle, Allen S., and Michael B. Letchworth. "Relationships Among Injury, Growth, and Yield Responses of Soybean Cultivars Exposed to Ozone at Different Light Intensities," Journal of Environmental Quality, Vol. 11 No. 4, 1982. 690-694.

"Four soybean cultivars (Glycine max (L.) Merr. cv. Forrest, Davis, Ransom, and Bragg) differing in foliar sensitivity and shoot weight response to ozone during vegetative growth were exposed to ozone from the seedling stage to maturity to determine if the yield response correlated with the vegetative response. Neither the foliar injury nor the vegetative shoot weight response of cultivars to ozone allowed reasonable prediction of the cultivar yield response to ozone. This inadequacy may relate to differences in cultivar tolerance. Bragg, with moderate amounts of ozone-induced injury and with decreased growth, yielded as well as the controls. Davis, with moderate amounts of ozone-induced injury and decreased growth, yielded 34 percent less than the controls. The four cultivars were grown in open-top field chambers with different degrees of shading to determine whether light intensity would alter their response to ozone. Light intensity in nonshaded open-top chambers was 9 percent less than that in an open field; chambers with shade cloth covering the sides or tops decreased light intensity by 15 and 19 percent, respectively. The shade treatments did not change overall yield response to ozone, or the relative cultivar yield response to ozone."

Further work is needed to develop a rapid screening technique to identify soybean cultivars tolerant to ozone and to combine this tolerance with high-yielding characteristics.

Heagle, Allen S., Robert B. Philbeck, Patricia F. Brewer, and Ronald E. Ferrell. "Responses of Soybeans to Simulated Acid Rain in the Field," Journal of Environmental Quality, Vol. 12, No. 4, October-December 1983. 538-543.

"Soybeans were grown in the field during 1979 and 1980 to determine whether the acidity of simulated rainfall would affect plant injury, growth, or yield, soil chemistry, soil nematode populations, and Rhizobium nodulation of roots. Plants were exposed twice weekly to 0.74 cm (1979) or 0.85 cm (1980) of simulated rain at pH levels of 5.5, 4.0, 3.2 or 2.8 in 1979 and



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5.4, 4.1, 3.2 or 2.4 in 1980. There were six 3-$m^2$ plots (replicates) for each pH level. Simulated rain at pH 2.8 or 2.4 caused small amounts of foliar injury evident as bifacial white or tan lesions primarily on young leaves. However, plant growth, pod yield, foliar elemental content, seed protein content, seed oil content, Rhizobium nodulation of roots, and populations of parasitic nematodes were not affected. Soil analyses were performed before, midway through, and after each season. Trends toward lower soil pH, and less Ca, Mg and K occurred with increased acidity of simulated rain. These effects were statistically significant only for soil pH, Mg, and K at treatment pH 2.4. Possible effets of ambient rain at current pH levels on agricultural soils are likely to require long-term deposition."

Heagle, A. S., R. B. Philbeck, and W. M. Knott. "Thresholds for Injury, Growth, and Yield Loss Caused by Ozone on Field Corn Hybrids," Phytopathology, Vol. 69, No. 1, 1979. 21-26.

"A commercial field corn (Zea mays L.) hybrid 'Coker 16' was exposed to four chronic doses of ozone in open-top field chambers from 25 days after planting until maturity. The different doses were obtained by adding different but constant concentrations of ozone to the naturally varying ambient concentrations for 7 hr/day (from 0930 to 1630 hours). The threshold ozone concentrations causing foliar injury (between 0.02 and 0.07 ppm) were lower than concentrations required to decrease kernel yield (between 0.11 and 0.15 ppm). These thresholds were the same whether plants were grown in pots or in the ground. In the greenhouse, the sensitivity of Coker 16 to growth effects caused by chronic ozone exposures was intermediate to that of two open-pedigree hybrids. In the field, both open-pedigree hybrids were more sensitive than Coker 16. Exposure to a mean ozone concentration of 0.15 ppm for 7 hr/day decreased kernel yield of the open-pedigree hybrids by 37-40% but that of Coker 16 was decreased by only 12%..."

Heagle, Allen S., Suzanne Spencer, and Michael B. Letchworth. "Yield Response of Winter Wheat to Chronic Doses of Ozone," Canadian Journal of Botany, Vol. 57, 1979. 1999-2005.

"The relative sensitivity of 11 soft red winter wheat (Triticum aestivum L.) cultivars, exposed as young plants to ambient levels of ozone ($O_3$) was determined. On the basis of the shoot dry weight response, the cultivar Holly was determined to be significantly more sensitive than Oasis or Coker 47-27; Blueboy II showed intermediate sensitivity. Plants of these four cultivars, grown in pots in the ground, were exposed for 54 days in open-top field chambers to different $O_3$ concentrations added to existing levels of ambient oxidants for 7 hr/day. The effects of $O_3$ on foliar injury, growth, and yield were determined. For the four cultivars combined, the



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threshold $O_3$ concentration (7 h/day seasonal mean) for significant injury and decreased growth and yield was between 0.06 and 0.10 ppm. For potted plants exposed to 0.10 and 0.13 ppm $O_3$, seed weight yields were 10 and 27 percent less, respectively, than for those grown in "charcoal-filtered-air" chambers (0.03 ppm $O_3$). For plants in the ground exposed to 0.10 and 0.13 ppm $O_3$, the yields were 16 and 33 percent less, respectively, than for those at 0.03 ppm $O_3$. The relative sensitivity of cultivars to $O_3$ as young plants could not be used to predict $O_3$ effects on seed yield."

Heath, Robert L. "Ozone," Response of Plants to Air Pollution. Ed. J. B. Mudd and T. T. Kozlowski. Academic Press, Inc., New York, 1975. 23-55.

Most air pollution work on plant species has shown that all species are not injured in the same or uniform manner "Exposure of very sensitive plants (for example, bean, tobacco, leafy vegetables, and some ornamentals) under the right conditions to ozone....will cause visible injury to appear on the leaf within the next few days....[C]ertain plants can now be used as monitoring devices for the presence of air pollutants....The minimal visible changes attributable to ozone injury are necrosis, chlorosis, and/or flecking of the upper leaf surface. These visible symptoms are thought to result by way of the following sequence of events: Ozone interaction with some component of cells in leaf tissue; collapse of cell and a general 'water logging'....in the vicinity of the interaction; bleaching of the chlorophyll within the injured cell; and breakdown of the leaf structure around the cell....The observation that leaves pass through a particular development stage during which they are extremely susceptible to ozone damage suggests that particular metabolic and/or physiological conditions exist which contribute to sensitivity. As these conditions are more precisely defined, it should be possible to prevent ozone injury by applying certain materials to retard injury, by developing particular strains or varieties of plants with minimal sensitivity or by genetic manipulations."

Heck, Walter W. and John A. Dunning. "Response of Oats to Sulfur Dioxide: Interactions of Growth Temperature with Exposure Temperature or Humidity," Journal of the Air Pollution Control Association, Vol. 28, No. 3, March 1978. 241-246.

"Three experiments were designed to determine the effects of $SO_2$ concentration on two oat varieties--Carolee and Coker 227. The plants were grown under uniform conditions prior to and after the experimental growth period. During the 7 to 14 day experimental growth period the plants were subjected to four growth temperatures and exposed 2 or 4 times to specific concentrations of $SO_2$ (0 to 4 ppm) for 1.5 or 3.0 hr periods. In the first two experiments, the exposure temperatures were varied (18° to 30°). In the third design, the exposure temperatures remained constant and two exposure relative humidities (55 and 80%) were used. Injury and growth reduction



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were more severe in Coker 227 than in Carolee. Root dry weight was affected more than top dry weight. Plants were more sensitive at higher growth temperatures but exposure temperatures had little to variable effects. Plants were more sensitive at 80% than at 55% relative humidity. Biomass was reduced at 0.4 ppm $SO_2$ after four 3 hr exposures and at 0.75 ppm after two 1.5 hr exposures, but growth was also increased as often. These concentrations approached the accepted threshold for adverse effects to sensitive vegetation. Foliar injury was highly correlated with growth reductions." Results of this research indicate that early spring $SO_2$ fumigations of oat will affect biomass less than exposure later in the year; cool periods during growth will favor plant resistance to $SO_2$ fumigation, and both test varieties will be very sensitive to an early morning $SO_2$ fumigation after a warm period.

Heggestad, H. E., and M. N. Christiansen. "Effects of Air Pollutants on Cotton," Effects of Air Pollution on Farm Commodities, Proceedings of the Symposium, Feb. 18, 1982. Izaak Walton League of America, Arlington, Virginia. 9-32.

The authors assess the impact of atmospheric concentrations of ozone and sulfur dioxide on cotton yields. The article examines and summarizes data from greenhouse experiments at Beltsville and from field experiments in California as well as other scientific literature. Secondary data are also reviewed. The authors estimate that California cotton yields are being reduced about 15 percent, primarily because of ozone pollution. Yields of sensitive cotton varieties may be reduced more, less sensitive variety yields reduced less.

Howell, R. K., L. P. Rose Jr., and R. C. Leffel. "Field Testing Soybeans for Residual Effects of Air Pollution and Seed Size on Crop Yield." Journal of Environmental Quality, Vol. 9, No. 1, 1980. 66-68.

Mean seed weights for four soybean cultivars grown in cylindrical open-top field chambers that provided carbon-filtered air were significantly greater than from plants grown in non-filtered air in chambers, or in conventional plots without chambers. "Using this seed an experiment was designed to address three questions: (1) Does air quality influence seed yields from subsequent plants? (2) Do seed size differences, possibly induced by air pollutants, influence subsequent seed yields? (3) Is there a yield advantage from planting large seed vs an original lot of seed? Results from the experiment indicated that there were no residual air quality effects on subsequent seed yields. Differences in seed size observed for different air qualities did not significantly affect yields. In general, there was no significant yield advantage for plants grown from a selected seed size as compared with the original seed lot."



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Hsieh, Tsun-shik Rossana. "Genetics and Physiology of Air Pollution Effects on Maryland Tobacco, Nicotiana Tabacum L.," Ph. D. dissertation, University of Maryland, 1974.

"The genetics and physiology of air pollution, primarily ozone effects, on Maryland tobacco were studied under greenhouse and field conditions.... Results from the greenhouse studies involving the exposure of seedling plants were in general agreement with the field results....Small and significant responses were found for yield per acre and value per acre in the field study, and air pollution susceptibility in the greenhouse.... Air pollution damage was associated with lower price per hundredweight.... and a reduction in yield and value per acre....Burning ability and filling capacity of the cured leaves were positively correlated with air pollution damage....[A] negative relationship between alkaloid levels in cured tobacco and air pollution susceptibility was observed."

Hughes, P. R., A. I. Dickie, and M. A. Penton. "Increased Success of the Mexican Bean Beetle on Field-Grown Soybeans Exposed to Sulfur Dioxide," Journal of Environmental Quality, Vol. 12, No. 4, October-December 1983. 565-568.

"Field planted soybeans were enclosed in screened cages and fumigated intermittently with $SO_2$ by means of a tube fumigation system. The plants were fumigated for a total of 191 hours over a 68 day period. One week after fumigation began, six pairs of newly emerged Mexican bean beetle adults were introduced into each of the cages. In less than one generation time, the mean number of progeny from these beetles feeding on fumigated plants was 1.5 times greater than that of beetles feeding on control plants. Larval growth was also significantly greater on the fumigated plants, especially for females. These crop X insect interactions which occur at low intermittent doses of $SO_2$ increase the potential impact of the insects on crop production."

Irving, Patricia M. and Joseph E. Miller. "Productivity of Field-Grown Soybeans Exposed to Acid Rain and Sulfur Dioxide Alone and in Combination," Journal of Environmental Quality, Vol. 10, No. 4, October-December 1981. 473-478.

"Sulfur dioxide fumigated and unfumigated field plots of soybeans (cultivar Wells) were exposed to acid (pH 3.1) or control (pH about 5.3) precipitation simulants to determine effects on growth and productivity. The precipitation simulants were applied at approximately 5-day intervals in July and August with a total of 3.4 cm applied in 1977 and 4.5 cm in 1978. Sulfur dioxide fumigations of 4 hour durations were performed 24 times in 1977 and 17 times in 1978, resulting in an average fumigation concentration of 0.79 ppm (89.6 ppm hour dose) sulfur dioxide the 1st year and 0.19 ppm (13.5 ppm hour) the 2nd. The acid precipitation simulant produced no statistically significant effect on seed yield in either year and a 4%



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increase in seed size in 1978. The simulated acid rain may have contributed to the nutritional requirements of soybeans by providing S and N during the critical pod-filling stage. Sulfur dioxide exposure decreased seed yields in both 1977 and 1978 by more than 35 and 12%, respectively. Accelerated senescence, as suggested by increased leaf fall, may be responsible for the decreased yield in the sulfur dioxide exposed plants."

"The sulfur dioxide exposure appeared to negate the positive acid rain effect on seed size observed in 1978, when the two treatments were combined. Acid precipitation apparently increased the reduction in seed weight resulting from sulfur dioxide exposure in 1977. Although visible injury was induced by acid rain exposure in a chamber study, only a small percentage (less than 1%) of tissue was affected and there was no apparent effect on plant growth. The results of these studies suggest that the possibility for harmful effects on soybean yield from acid precipitation of a magnitude used in this study are minimal; however, soybean yields may be decreased by sulfur dioxide exposures greater than 13.5 ppm hour occurring during the growing season."

Irving, Patricia M., Joseph E. Miller, and Patricia B. Xerikos. "The Effect of $NO_2$ (Nitrogen Dioxide) and $SO_2$ (Sulfur Dioxide) Alone and in Combination on the Productivity of Field-Grown Soybeans," Air Pollution by Nitrogen Oxides. Ed. T. Schneider and L. Grant, Elsevier Scientific Publishing Co., Amsterdam, 1982. 521-531.

"Investigations of effects on plants from single pollutants are numerous and provide useful determinations of phytotoxicity levels; however, pollutants rarely occur alone, and field investigations of pollutant combinations are limited. Combustion processes which generate sulfur dioxide usually produce a mixture of nitrogen oxides, as demonstrated by ambient air monitoring data. In order to determine the effects of pollutant combinations on crop plants, field investigations were conducted in 1980 and 1981 using soybeans (Glycine max L.) exposed to sulfur dioxide and nitrogen oxides alone and in combination, in the presence of ambient ozone."

"Open-air field plots of soybeans were fumigated with sulfur dioxide and nitrogen dioxide through a system of aluminum pipes suspended above the plant canopy, utilizing the ZAPS (Zonal Air Pollution System) design. After being released from the pipe, the pollutant gas concentrations decreased with distance downwind from the pipe as a result of normal turbulent dispersion."

"In both years of the study, the soybean plots were fumigated on 10 occasions during the pod-filling period for an average exposure time during fumigation of three hours. Mean concentrations during fumigation periods ranged from 0.13 to 0.42 ppm of sulfur dioxide and 0.06 to 0.40 ppm of nitrogen dioxide."



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"Results from both years of the experiment indicated that fumigations with nitrogen dioxide alone had no effect on seed yields. Exposures with sulfur dioxide alone had no effect on yields in 1980 and decreased yields up to 6 percent in 1981. Combinations of sulfur dioxide and nitrogen dioxide had a synergistic effect both years of the study and resulted in yield decreases ranging from 9 to 25 percent."

Jacobson, Jay S. "A Comparison of Four Field Experiments with Soybeans and Simulated Rain," Proceedings: Atmospheric Deposition Specialty Conference. Ed. Edward R. Frederick. Conference held Nov. 7-10, 1982, Detroit. Air Pollution Control Association, Pittsburgh, 1983. 367-378.

"Four field experiments in which acidic rain was applied to soybeans (Glycine max [L.] Merr.) have been analyzed in order to: 1) Compare effects on seed yield; 2) determine similarities and differences in approaches; 3) determine whether general conclusions can be drawn concerning the impact of acidic rain on soybean productivity; and 4) make recommendations concerning future experimental investigations on this subject. Material for these comparisons was obtained from publications and manuscripts describing results of studies performed at four different locations in the eastern and midwestern United States....Data from field experiments performed at Brookhaven, N. Y. (Long Island), Argonne, Illinois, Raleigh, North Carolina, and Yonkers, N. Y. were analyzed and compared...."

"Although experiments were similar in their use of a single crop species, exposure to simulated acidic rain, and measurement of growth and yield, results were entirely discordant. In one study, yield decreased; in another, yield increased; and in two studies, yield was not significantly affected by changes in acidity of simulated rain. More detailed comparisons indicate that major differences existed between studies in the following categories: Soybean cultivars, cultural conditions, soil characteristics, addition of fertilizer and use of pesticides, ambient environmental conditions, acceptance or exclusion of ambient rain and ozone, procedures and techniques for application of simulated rain, chemical composition of simulated rain, experimental design, and statistical methods. Conclusions from these field experiments cannot be drawn concerning the effect of acidic rain on yield of soybeans not only because results were different but also because those differences cannot be associated with specific differences in approaches, methods, techniques, and procedures. Each study contained important advantages that should be retained and significant limitations that should be avoided in future research. Unfortunately, some advantages and limitations are mutually inclusive."



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Jacobson, Jay S. and Luke Colavito. "The Combined Effect of Sulfur Dioxide and Ozone on Bean and Tobacco Plants," Environmental and Experimental Botany, Vol. 16, No. 4, December 1976. 277-285.

"Plants of two cultivars of Phaseolus vulgaris L. (bean) and Nicotiana tabacum L. (tobacco) were exposed to a replicated series of concentrations of sulfur dioxide ($SO_2$), ozone ($O_3$), and combinations of these two air pollutants. Experiments were performed in controlled-environment chambers using concentrations of pollutants above and below Federal ambient air quality standards in order to determine whether interactive effects result from exposure to concentrations of pollutants occurring in some agricultural areas of the United States. Dose-response functions were determined for $SO_2$ and $O_3$, alone and in combination, by transforming incidence of foliar injury into probit units and presenting the data as logarithmic functions of dose. In bean cultivars, the toxicity of $SO_2$ or $O_3$ was either attenuated or not affected when the two pollutants were combined, depending upon their concentrations. In tobacco, the toxicity of $SO_2$ or $O_3$ was either amplified or not affected in the presence of the two pollutants. Concentrations of $SO_2$ or $O_3$ that did not exceed the respective U.S. ambient air quality standards significantly altered the incidence of injury caused by the other pollutant. These results demonstrate that interactive effects between $SO_2$ and $O_3$ can occur but the magnitude and direction of these effects depend on plant species and concentrations of pollutants."

Jacobson, J. S., J. Troiano, L. J. Colavito, L. I. Heller, and D. C. McCune. "Polluted Rain and Plant Growth," Polluted Rain. Ed. T. Y. Toribara, M. W. Miller, and P. W. Morrow. Proceedings of the Twelfth Rochester International Conference on Environmental Toxicity, University of Rochester, held May 21-23, 1979. Plenum Press, New York, 1980. 291-305.

"Experiments were performed to determine whether the effects of acidic precipitation on agricultural crops of the eastern U.S. are altered by differences in the supply of nitrate and sulfate in rain or the concentration of ozone in the atmosphere....Differences in bean yield were not significantly affected by acidity of simulated rain either for the low or high ozone exposures. However, exposure to elevated concentrations of ozone depressed both growth and yield of soybeans with all three rain treatments and the depression was greatest with the most acidic rain....Although this report emphasizes the potential significance of the nutrient supply of precipitation, it is important to recognize that the loss of nutrients from plants by leaching also has been known for more than 70 years...The balance between uptake and loss of nutrients in plants exposed to rain depends on biological, environmental, and temporal factors that vary with geographical location and the individual rain event...."

"Our results indicate that both the exposure of plants to nitrate and sulfate in rain and to ozone in the atmosphere are important factors to consider when determinations are made of the effects of acidic precipitation on vegetation.



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The qualitative character and magnitude of effects of acidic precipitation may change with different conditions of plant nutrition and air pollution. Future experiments should be performed with these factors controlled or carefully measured before a full understanding of the effects of acidic precipitation on vegetation can be obtained."

Jones, U. S. and E. L. Suarez. "Impact of Atmospheric Sulfur Deposition on Agroecosystems," Atmospheric Sulfur Deposition: Environmental Impact and Health Effects. Ed. D. Shriner, C. Richmond, and S. Lindberg. Proceedings of the Second Life Sciences Symposium, Gatlinburg, Tennessee, October 14-18, 1979. Ann Arbor Science, Ann Arbor, Michigan, 1980. 377-396.

"In South Carolina, sulfur supplied in precipitation increased from an annual average of 6.3 kg/ha in 1953-1955 to 11.3 kg/ha in 1973-1975. Annual sulfur fallout in precipitation in Iowa, Tennessee, and Wisconsin rural areas during the 1970s was about twice that in South Carolina. Twenty years ago, sulfur in the atmosphere made a minor contribution to the sulfur required by agroecosystems in South Carolina, but current data indicate that it now makes a major contribution....At the present rural levels of air sulfur dioxide and subsoil sulfate, the possibility that plant health of eastern U.S. agroecosystems is being influenced by too much or too little atmospheric sulfur is slight."

Kress, Lance W. "Effects of Air Pollutants on Corn," Effects of Air Pollution on Farm Commodities. Proceedings of the Symposium, February 18, 1982. Izaak Walton League of America, Arlington, Virginia. 91-101.

The author assesses the impact of atmospheric concentrations of ozone, sulfur dioxide and nitrogen dioxide on yield and growth of corn. Data from both greenhouse and field experiments are employed. Two common field corn hybrids, PAG-397 and Pioneer 3780, were planted in open-top chambers. These varieties in chambers with ozone concentration averaging .06 ppm yielded almost the same as the same varieties in chambers with charcoal-filtered air (the controls, at about .025 ppm). However, PAG-397 exposed to .10 ppm yielded 10 percent less than the PAG control, and Pioneer 3780 at the same exposure yielded 22 percent less that the Pioneer control. (Thus, corn yield reduction with higher ozone exposure traces a nonlinear function.) Higher doses of ozone produced even greater yield loss. Sweet corn tends to be more sensitive to ozone than field corn.

Because the threshold for yield reduction for corn appears to be above .06 ppm ozone, corn is less sensitive to this pollutant than soybeans, which display yield reduction from ozone even between .025 and .06 ppm. In general, exposure of corn to ozone or sulfur dioxide tends to increase the susceptibility of the plant to disease.



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Kress, L. W., and J. E. Miller. "Impact of Ozone on Soybean Yield," Journal of Environmental Quality, Vol. 12, No. 2, April-June 1983. 276-281.

"Based on this study, ambient ozone concentrations appear to be capable of having a significant effect on the yield of soybean plants. A significant linear regression indicated that soybean seed yield was reduced 11% in our experiment, due to the 1980 ambient ozone (0.042 ppm for a 7-hr daily seasonal average) at the experimental site when compared with a 0.022 ppm control treatment. The total reduction in yield was the result of fewer filled pods per plant, fewer seeds per filled pod, and smaller seeds. Two other studies with other cultivars of soybeans (Heagle and Heck, 1980; Kohut et al., 1982) have also produced similar negative linear correlations between ozone and yield of soybeans, with indications of loss in productivity at ambient ozone concentrations that occur in many soybean production regions. It appears that further reductions in yield would occur with increased ozone concentrations, while higher yields would result if concentrations were reduced."

Krupa, S. V., B. I. Chevone, J. L. Bechthold, and J. L. Wolf. "Vegetation: Effects of Sulfur Deposition by Dry-Fall Processes," Atmospheric Sulfur Deposition: Environmental Impact and Health Effects. Ed. D. Shriner, C. Richmond, and S. Lindberg. Proceedings of the Second Life Sciences Symposium, Gatlinburg, Tennessee, October 14-18, 1979. Ann Arbor Science, Ann Arbor, Michigan, 1980. 309-320.

"The results of a four-year study of atmospheric sulfur inputs and effects on terrestrial vegetation relative to a coal-fired power plant were reviewed. The power plant is located near Becker, Minnesota and is surrounded by a highly agricultural and irrigated area. Dry-fall and wet-fall inputs of sulfur into cornfields in the vicinity of the point source were calculated to be 0.82 and 4.41 kg/ha, during the crop season. High sulfur inputs through wet-fall in the study area seem to be attributable to long-distance transport of $SO_4$. No visible $SO_2$ - induced vegetational injury was observed over an 80-km radius around the point source during the four years of power plant operation. Foliar sulfur concentrations were determined in several plant species. A plot-by-plot analysis over the four years showed increased foliar S ($R^2 = 0.87$) in 17 of the 48 permanent plots independent of the plant species in the plot. The increased foliar sulfur content is still within the norm of foliar concentrations reported for each individual species. It is suggested that the increase in foliar sulfur is due to the incremental dry fall of atmospheric sulfur."



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Lang, David S., Sagar V. Krupa, and David S. Shriner. "Injury to Vegetation Incited by Sulfuric Acid Aerosols and Acidic Rain," Proceedings of the 7th Annual Meeting of the Air Pollution Control Association, Houston, Texas, June 25-30, 1978. Paper No. 78 - 7.3. Published by the Air Pollution Control Association, Pittsburgh.

"A system for exposing vegetation to submicron sulfuric acid aerosol has been described. This facility has proved effective in maintaining submicron aerosol distributions which appear to be uniform as measured by physical and biological indices. Five plant species have been examined and classified according to relative susceptibility to submicron sulfuric acid aerosol injury. All species examined have shown the same characteristic symptoms of marginal and tip necrosis during acute exposures. Attempts have been made to correlate effects associated with chronic exposure and macrosymptom expression but have not yet proven successful..."

"Numerous small areas of bifacial necrosis on the leaves are characteristic symptoms of simulated acidic rain (pH 3.2) injury on oak. Cuticular leaf surface waxes are eroded by this treatment. This may have an important influence on water relations, protection against stress and radiation balance."

Lauenroth, W. K. and J. E. Heasley. "Impact of Atmospheric Sulfur Deposition on Grassland Ecosystems," Atmospheric Sulfur Deposition: Environmental Impact and Health Effects. Ed. D. S. Shriner, C. R. Richmond and S. E. Lindberg. Proceedings of the Second Life Sciences Symposium, Gatlinburg, Tennessee, October 14-18, 1979. Ann Arbor Science, Ann Arbor, Michigan, 1980. 417-430.

Impacts of sulfur deposition on grassland ecosystems, focusing upon carbon flow and nutrient cycling, were examined. "The results of field and laboratory experiments indicate that excess sulfur entering the system as sulfur oxides results in the reduction of chlorophyll in the dominant primary producer species. The most immediate impact of exposure to low concentrations of $SO_2$ is the increase in sulfur content in all the ecosystem components. Changes in primary producer sulfur content may reduce the palatability of certain species for herbivores, thus reducing herbivore numbers or causing a shift in grazing pressure to more palatable species....

"Changes in grazing pressure together with differential tolerance for excess sulfur could result in a shift in species composition in all biotic components of the grassland ecosystem. Perhaps the most significant impact of sulfur deposition in the long run may be the impact upon decomposition processes. Because of reduced decomposition, a larger portion of the potentially available nutrients will be tied up in organic matter.... The turnover rate of nonsulfur nutrients should be rapid but low in volume due to lower decomposition rates. Decomposer carbon will be decreased as a result of $SO_2$ input....Consumer carbon will be decreased as a result of decreased primary production."



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Lee, Jeffrey J., Grady F. Neely, Shelton C. Perrigan, and Louis C. Grothaus. "Effect of Simulated Sulfuric Acid Rain on Yield, Growth, and Foliar Injury of Several Crops," Environmental and Experimental Botany, Vol. 21, No. 2, 1981. 171-185.

"This study was designed to reveal patterns of response of major United States crops to sulfuric acid rain. Potted plants were grown in field chambers and exposed to simulated sulfuric acid rain (pH 3.0, 3.5 or 4.0) or to a control rain (pH 5.6). At harvest, the weights of the marketable portion, total aboveground portion, and roots were determined for 28 crops. Of these, marketable yield production was inhibited for 5 crops (radish, beet, carrot, mustard greens, broccoli), stimulated for 6 crops (tomato, green pepper, strawberry, alfalfa, orchardgrass, timothy), and ambiguously affected for 1 crop (potato). In addition, stem and leaf production of sweet corn was stimulated. Visible injury of tomatoes might have decreased their marketability. No statistically significant effects on yield were observed for the other 15 crops. The results suggest that the likelihood of yield being affected by acid rain depends on the part of the plant utilized, as well as on species. Effects on the aboveground portion of crops and on roots are also present. Plants were regularly examined for foliar injury associated with acid rain. Of the 35 cultivars examined, the foliage of 31 was injured at pH 3.0, 28 at pH 3.5, and 5 at pH 4.0. Foliar injury was not generally related to effects on yield. However, foliar injury of swiss chard, mustard greens and spinach was severe enough to adversely affect marketability."

Manning, William J. "Interactions Between Air Pollutants and Fungal, Bacterial and Viral Plant Pathogens," Environmental Pollution, Vol. 9, 1975. 87-90.

Interactions between air pollutants, plants, and microbial plant pathogens can affect pathogenesis. "Pollutants may have direct effects on microbial pathogens during a critical stage of infection or reproduction. Plant susceptibility to microbial pathogens may be altered by air pollutants. Pollutants may also affect the microflora associated with plant surfaces which may, in turn, affect disease development." The author outlines current knowledge by summarizing some observations and experiments that have been reported for interactions between ozone, sulphur dioxide, fluoride, particulates and fungi, bacteria and viruses that cause plant diseases. Although a number of observations have been made on the effects of ozone and sulphur dioxide on diseases caused by fungi, relatively little is known about the effects these pollutants may have on diseases caused by bacteria, viruses and nematodes.



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Medeiros, W. H., P. D. Moskowitz, E. A. Coveney, H. C. Thode, Jr., and N. L. Oden. "Oxidant and Acid Precipitation Effects on Soybean Yield: Cross-Sectional Model Development," Environment International, Vol. 10, 1984. 27-33.

"Regression models have been constructed to examine effects of oxidant and acid precipitation air pollutants and regional factors on soybean yield. Although regional factors provide most of the explanatory power, effects of oxidants and acid precipitation are statistically significant. These regressions suggest that controlling oxidant air pollution may produce greater benefit than controlling acid precipitation. Specifically, controlling pH to 5.2 or 5.6 would result in a national-level increase in soybean yield of about 1%. In comparison, if oxidant concentrations were controlled to 40 or 25 ppb...., a national level increase of 4% to 9% is predicted. Simultaneous control of both pollutants (that is, pH = 5.6, oxidant = 25 ppb) would result in a national-level benefit of about 10%. Regression models and field generated dose-response functions predict similar results. Before the methods developed in this paper can be used for policy analysis, data and sources of estimate uncertainty need to be more closely examined."

Menser, H. A., G. H. Hodges and C. G. McKee. "Effects of Air Pollution on Maryland (Type 32) Tobacco," Journal of Environmental Quality, Vol. 2, No. 2, 1973. 253-258.

"Six Maryland tobacco cultivars were tested for resistance to air pollutants. Fumigation chamber tests disclosed that ozone used at 5 pphm for six hours destroyed 5-10 percent of the leaves. Ozone administered for 3 hours at 15 pphm damaged about one-third of the leaves and injured about two-thirds of the leaf surfaces when concentration was increased to 30 pphm....Ozone and sulfur dioxide mixtures acted synergistically to inflict ozone-type symptoms on all Maryland cultivars. No injury resulted when plants were fumigated singly for 4 hours with ozone at 3 to 3.5 pphm and sulfur dioxide at 45 to 50 pphm. The combination of these gases at the same concentrations and time interval produced 5 to 15% leaf injury. Twice as much injury occurred when mixed gases were used for 2 hours at 10 to 12 pphm ozone and 45 to 50 pphm sulfur dioxide. Sulfur dioxide injury thresholds were barely reached by a 3 hour exposure at 150 pphm....Field studies in the five-county Southern Maryland District disclosed a general correlation between resistance to ozone and resistance to sulfur dioxide....The severity of symptoms on Maryland cultivars and on fleck-susceptible cultivars suggested that during periods of air stagnation, oxidants probably exceed 10 pphm throughout most of the Type 32 area, and are responsible for most of the fleck damage."



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Miller, Joseph E. "Effects of Air Pollutants on Soybeans," Effects of Air Pollution on Farm Commodities. Proceedings of the Symposium, February 18, 1982. Izaak Walton League of America, Arlington, Virginia. 57-77.

The author assesses the impact of atmospheric concentrations of ozone, sulfur dioxide and nitrogen oxides on yield and growth of soybeans. Data from many greenhouse and field experiments are used. The author concludes that soybeans are relatively sensitive to most of the common gaseous air pollutants, especially ozone. Different soybean varieties respond in differing degrees to the same ozone concentrations. However, allowing for the range of varietal response, field experiments show that a change of ozone concentration of .01 ppm in either direction tends to alter soybean yield by 3 to 6 percent, the greater the ozone concentration, the greater the yield reduction; correspondingly, the lesser the ozone concentration, the greater the yield increase. Since it is not unusual for seasonal average ambient ozone levels in soybean growing regions to be found between .04 and .07 ppm, even this range of variation could influence soybean yield significantly. In addition, ozone can aid the development of plant disease on soybeans.

Muller, R. N., J. E. Miller, and D. G. Sprugel. "Photosynthetic Response of Field Grown Soybeans to Fumigations with Sulfur Dioxide," Journal of Applied Ecology, Vol. 16, 1979. 567-576.

"(1) Field-grown soybeans were exposed to three levels of sulfur dioxide to determine the effects of the exposure upon photosynthesis and stomatal resistance. (2) In plots where the mean sulfur dioxide concentration averaged about 790 ppb, photosynthesis was reduced to 37-63% of the control and, in plots where sulfur dioxide concentration averaged 120 ppb photosynthesis ranged from 90-137% of the control. (3) Stomatal resistance generally increased in the treated plants; however, the response lagged considerably behind the photosynthetic response, suggesting that stomatal closure did not cause the the observed reduction in photosynthesis. (4) Visible injury of the leaf tissue was observed only in the high treatment plot. The significant depression of photosynthesis in plots receiving about 300 ppb sulfur dioxide suggests that sulfur dioxide may reduce productivity without visible symptoms of injury."

Noggle, J. C. and H. C. Jones. "Effects of Air Pollutants on Wheat and Grains," Effects of Air Pollution on Farm Commodities. Proceedings of the Symposium, February 18, 1982. Izaak Walton League of America, Arlington, Virginia. 79-90.

The authors assess the impact of atmospheric concentrations of ozone, sulfur dioxide and fluorides on yields and growth of wheat. Data from greenhouse and field experiments are used. The authors conclude that ozone concentrations in the most heavily polluted regions can damage wheat grown there.



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According to one field experiment, performed in North Carolina with open-top growth chambers, exposure of wheat to ambient ozone averaging .06 ppm reduced yields by 4 percent; exposure at .13 ppm reduced yields by 33 percent. However, most of the U.S. wheat crop escapes ozone damage because of being grown in less polluted regions.

Norby, R. J. and R. J. Luxmoore. "Growth Analysis of Soybean Exposed to Simulated Acid Rain and Gaseous Air Pollutants," The New Phytologist, Vol. 95, No. 2, October 1983. 277-288.

"Greenhouse-grown soybean plants [cultivar Davis] were exposed to simulated acid rain (pH 2.6 to 5.6) and gaseous air pollutants (SO2 + 03) to determine how effects on short-term physiological processes are integrated into wholeplant response. Injury to expanding leaves, characterized by marginal necrosis and leaf deformation, was induced by twice-weekly exposure to simulated rain of pH 2.6 and to a lesser extent pH 3.4. Growth inhibition resulted only from exposure to rain of pH 2.6, and there were no significant pH x air pollution interactions....These experiments suggest that vegetative growth of soybeans may be adversely affected by acid rain if pH is low enough to cause physical injury to leaves and loss of photosynthetic area...."

"These experiments were not meant to substitute for field experiments. Possible effects of acid rain on flowering and seed yield were not considered. Plants grown under agronomic conditions may be less susceptible to acid rain-induced foliar injury and yield reduction than greenhouse-grown plants....The results should be useful, however, for interpretation of responses of soybeans in the field. Growth inhibition of soybeans from simulated acid rain was shown to occur only because physical damage to leaves at low pH lowered photosynthetic area. Assessment of crop losses in the field resulting from acid precipitation would be much easier if only visible foliar injury need be evaluated, although foliar injury has not been shown to occur at the pH levels found in natural precipitation. The physical characteristics of leaves that affect aggregation of raindrops, injury to cells, and continued leaf expansion may be the critical factors in determining the sensitivity of plants to acid precipitation."

Oshima, R. J., P. K. Braegelmann, R. B. Flagler, and R. R. Teso. "The Effects of Ozone on the Growth, Yield, and Partitioning of Dry Matter in Cotton," Journal of Environmental Quality, Vol. 8, No. 4, 1979. 474-479.

"Cotton was grown in an activated carbon-filtered greenhouse and exposed to biweekly ozone fumigations. Two ozone treatments were used, differing in age at initial exposure and total ozone dose. Sacrificial harvests were taken from all treatments at 14-day intervals to monitor plant response and to provide the basis for growth analysis techniques. Ozone reduced total



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plant yield (in terms of number of bolls and fiber, seed, residue, and total boll weights) an equivalent amount in both ozone treatments. The dry weights of all partitioned plant parts were reduced with the largest reductions occurring in roots and bolls. Fumigated plants initially produced fewer leaves with significantly less leaf area. A period of stimulated leaf and branch production followed the initial growth depression. Boll production was depressed 48 percent in both ozone treatments. Mean relative growth rates of partitioned plant parts were extremely good predictors of absolute responses."

Oshima, R. J., M. P. Poe, P. K. Braegelmann, D. W. Baldwin and V. Van Way. "Ozone Dosage-Crop Loss Function for Alfalfa: A Standardized Method of Assessing Crop Losses from Air Pollutants," Journal of the Air Pollution Control Association, Vol. 26, No. 9, September 1976. 861-865.

"Ozone-dose/crop-loss conversion functions for alfalfa....yield reduction and defoliation were developed using standardized field plots with an ambient $O_3$ gradient in the [California] South Coast Air Basin....Alfalfa yields and the defoliation index values were entered into a multiple regression program with seasonal $O_3$ doses, average season minimum and maximum temperatures, and average daily relative humidity values to determine significant correlationsand interactions....Ozone dose was the only monitored variable directly correlated with reduced seasonal yields and leaf/total weight ratios....Ozone dose-response conversion functions.... were....calculated using the dose-yield and dose-defoliation functions as a basis for the conversion to percent reduction....The predicted percent reduction value is easily converted to yield in terms of tons/acre which can in turn be translated into economic units. The defoliation function would require more sophisticated calculation since it is basically correlated to quality of harvest in terms of fiber content and would affect the price per unit of yield."

Oshima, R. J., O. C. Taylor, P. K. Braegelmann and D. W. Baldwin. "Effects of Ozone on the Yield and Plant Biomass of a Commercial Variety of Tomato," Journal of Environmental Quality, Vol. 4, No. 4, 1975. 463-464.

"A commercial variety of pole tomato was exposed to 20 and 35 parts per hundred million (pphm) ozone for 2.5 hours, 3 days each week over a period of 15 weeks. Extensive foliar injury, defoliation, and highly significant reductions in plant biomass occurred at both exposure levels. However, fruit yield was significantly reduced at only the higher 35 pphm ozone concentration. This reduction was due to a decrease in the number of fruit and not to a decrease in fruit weight. Fruit yield in the 20 pphm treatment was equal to that of the control despite a 27 percent reduction in total dry weight of plants. These results indicate the presence of a threshold for the effect of ozone on yield."



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Prasad, B. J., and D. N. Rao. "Effects of $SO_2$ Exposure on Carbohydrate Contents, Phytomass and Caloric Values of Wheat Plants," Water, Air, and Soil Pollution, Vol. 16, No. 3, 1981. 287-291.

"This paper reports the results of wheat plants exposed to $SO_2$. The $SO_2$-treated and control plant samples were periodically analyzed with respect to their carbohydrate content, caloric values, phytomass accumulations and net primary productivity. An initial increase, but later decrease, in all these parameters was recorded in $SO_2$ treated plants....[These] changes in carbohydrate contents, caloric values, dry matter accumulations and net primary produtivity of $SO_2$ treated plants may be hypothetically interpreted in terms of functional changes in the energy budget of plants stressed by $SO_2$ pollution. It is hypothesized that in response to $SO_2$ toxicity, material and chemical energy in wheat plants was diverted from sites of growth and storage to sites where repair was needed....Such a diversion of materials would hamper the net productivity of $SO_2$ treated plants."

Pratt, Gregory C. and Sagar V. Krupa. "Soybean Cultivar Hodgson Response to Ozone," Phytopathology, Vol. 71, No. 11, 1981. 1129-1132.

"The response of a plant to ozone should be related to variations in the concentration of pollutant, the exposure time, the age of the plant, the environmental conditions before, during, and after exposure, and any genetic differences in the sensitivity of the plant population. In the authors' study, environmental and genetic variations were minimized by use of environmentally controlled growth and exposure conditions and a single test cultivar.

"The log-probability model of Larsen and Heck was applied to visible injury data. With this model, visible injury to soybean cultivar Hodgson is predictable based on the pollutant concentration and exposure duration." [In general, the greater the concentration and exposure combined, the greater the injury.] "In comparison with the modeled responses of other crops, soybean cultivar Hodgson is relatively susceptible to ozone-induced visible injury. Using ambient ozone concentration data from a given location, Larsen and Heck have proposed that it may be possible to predict the level of ozone-induced injury that will occur under appropriate environmental conditions on crops grown in that area.

"Defoliation of soybean leaves during the growing season was related to yield, and the yield can be reduced significantly when the reduction in photosynthetic surface occurs during or immediately before the pod-filling stage. If pollutant concentrations are sufficient to produce visible symptoms and thereby reduce photosynthetic surface area, a decrease in yield is possible. Most soybeans have a determinate reproductive cycle, but cultivar Hodgson and some others have indeterminate reproductive cycles and flower and fruit over a longer period. Thus, under field conditions where episodic high concentrations of ozone occur, a longer period for potential yield effects exists with these indeterminate cultivars."



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"A decrease in leaf chlorophyll concentration occurred in soybean plants fumigated with low concentrations of ozone over several days. In these plants, visible symptoms were few or absent or consisted of a generalized chlorosis that was distinguishable only by careful comparison with controls or by measurement or leaf chlorophyll concentration. This loss in photosynthetic potential may also affect the efficiency of plant biomass production without being directly observable. Ambient atmospheric conditions in soybean-growing regions of Minnesota often include low concentrations of ozone for weeks or months with intermittent hourly peaks of higher concentrations. The results reported here suggest that such a pattern of exposure to ozone could affect soybean growth."

Reinert, R. A., D. S. Shriner, and J. O. Rawlings. "Response of Radish to All Combinations of Three Concentrations of Nitrogen Dioxide, Sulfur Dioxide, and Ozone," Journal of Environmental Quality, Vol. 11, No. 1, 1982. 52-57.

"The two experiments reported here represent an approach to understanding the combined effects of nitrogen dioxide, sulfur dioxide, and ozone. The experimental design has not been previously considered in pollutant-combination effects research and offers a way to address the following:

(1) The influence of subinjury threshold concentrations of two pollutants (nitrogen dioxide and sulfur dioxide) on plant response to a third pollutant (ozone);

(2) the dose response of two pollutants (sulfur dioxide and nitrogen dioxide, below, slightly above, and much above visible-injury threshold concentration) averaged over a third pollutant, nitrogen dioxide, at three concentrations below visible-injury thresholds;

(3) the effects of biomass change of varying ratios of one pollutant to two others, and

(4) an evaluation of the dose-response surface for radish foliage and root weight and an analysis of the linear and curvilinear components."

"Each of these considerations was partially or wholly addressed using a sensitive biomass-response measure, radish root fresh and dry weight. However, data should not be interpreted as being representative of a large range of plant species."

"Finally, using the growth parameters selected in this study, we conclude that radish root weight was a sensitive indicator of plant response. For the radish, this parameter happens to be of economic importance as well. As ozone concentrations increased relative to concentrations of nitrogen dioxide or sulfur dioxide, greater economic yield (radish hypocotyl fresh weight) reduction occurred as a general phenomemon. However, the relative importance of the increasing ozone concentration decreased as either sulfur dioxide or nitrogen dioxide concentration increased. Our results indicate that and understanding of mechanisms of plant response to pollutant combinations is needed if we are to predict effectively the magnitude and direction of plant effects resulting from exposure to two or more pollutants."



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Rich, Saul, Gordon S. Taylor, and Harley Tomlinson. "Crop Damaging Periods of Ambient Ozone in Connecticut," Plant Disease Reporter, Vol. 53, No. 12, December 1969. 969-973.

Symptoms of ozone toxicity have been found in Connecticut on alfalfa, broad beans, green beans, carrots, celery, cucumber, gourd, oats, parsley, parsnip, petunia, pine, potato, radish, spinach, squash, and tomato. "Plant damage in Connecticut is likely to occur whenever the ambient ozone reaches or exceeds 5 pphm for 1 hr or more. During the growing seasons of 1963-1967, 355 days were monitored. Of these, there were 83 polluted days, or 1 polluted day for every 4 days monitored. Of the 317 hours of high ozone recorded, 80% occurred in the afternoon. There was no indication that pollution by ambient ozone became progressively more severe during the period 1963-1967."

Richards, G. A., C. L. Mulchi, and J. R. Hall. "Influence of Plant Maturity on the Sensitivity of Turfgrass Species to Ozone," Journal of Environmental Quality, Vol. 9, No. 1, 1980. 49-53.

Sensitivities of turf species to different doses of ozone at several stages of plant development were evaluated. "Warm and cool season turfgrass species and cultivars were exposed in fumigation chambers to various concentrations of ozone and scored for vegetative damage. The warm season entries (Meyer zoysia grass and Tufcote bermuda grass) exhibited greater tolerance to ozone than the cool season entries (tall fescue, perennial ryegrass, bent grass, red fescue, Kentucky bluegrass, and annual bluegrass)... Increasing the ozone exposure from 3.5 to 7.0 hours/day at 0.1 ppm caused twice the level of vegetative damage. As a group, seedlings 9 to 14 days of age exhibited greater susceptibility and uniformity in treatment response than seedlings 66 to 71 days of age to ozone exposure of 0.3 to 0.5 ppm for 3 hours."

Shriner, D. S. "Effects of Simulated Rain Acidified with Sulfuric Acid on Host-Parasite Interactions," Proceedings of the First International Symposium on Acid Precipitation and the Forest Ecosystem, Columbus, Ohio, May 12-15, 1975. Ed. L. S. Dochinger and T. A. Seliga. Forest Service General Technical Report NE-23. Forest Service, USDA, 1976. 919-925.

"Wind-blown rain, rain splash and films of free moisture play important roles in the epidemiology of many plant diseases. The effects of simulated rain acidified with sulfuric acid were studied on host-parasite systems. Plants were exposed in greenhouse or field to simulated rain of pH 3.2 $\pm$ 0.1 or pH 6.0 $\pm$ 0.2....Five host-parasite systems were investigated. In three of these five cases, significant inhibition of some parameter of disease development occurred." [at the pH 3.2 exposure compared to the pH 6.0]



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Shriner, D. S. "Vegetation Surfaces: A Platform for Pollutant/Parasite Interactions," Polluted Rain. Ed. T. Y. Toribara, M. W. Miller, and P. E. Morrow. Proceedings of the Twelfth Rochester International Conference on Environmental Toxicity, University of Rochester, Rochester, New York, May 21-23, 1979. Plenum Press, New York, 1980. 259-272.

"This paper discusses examples of pollutant-parasite interactions at the leaf surface to illustrate the role that pollutants can play in the relationship of susceptible host and virulent pathogen....Above-ground surfaces of higher plants are the site of deposition of a variety of airborne biological materials and atmospheric pollutants. These biological materials (pollen, fungal spores, bacterial cells, waste from insect feeding) and the pollutants (as aerosols, gases, or dissolved in rain) may interact to influence the host plant, the pathogen, or the host/pathogen association." Generalizations about host/parasite/pollutant interactions are different. The sensitivity of the host plant, the type of pathogen, the type and dose of pollutant, as well as other critical variables must first be known.

Shriner, D. S., and E. B. Cowling. "Effects of Rainfall Acidification on Plant Pathogens," Effects of Acid Precipitation on Terrestrial Ecosystems. Ed. T. C. Hutchinson and M. Havas, Proceedings of the NATO Conference on Effects of Acid Precipitation on Vegetation and Soils, held in Toronto, Canada, May 21-27, 1978. Plenum Press, New York, 1980. 435-442.

Acid rain or particulate matter deposited on the leaves of plants can be a critical factor in making an attack by pathogenic fungi or bacteria more damaging. On the one hand, acidity tends to weather or injure leaf surfaces, making them more vulnerable to attack by pathogens. On the other hand, growth of some fungi on foliage is inhibited by foliage water droplets in the pH 4.1-3.2 range. Many kinds of interactions between dry or wet acidic deposition and plant pathogens are still unknown.

Shriner, D. S., and J. W. Johnston. "Effects of Simulated, Acidified Rain on Nodulation of Leguminous Plants by Rhizobium Species," Environmental and Experimental Botany, Vol. 21, No. 2, 1981. 199-209.

"Simulated rain acidified with sulfuric acid to pH 3.2 inhibited Rhizobium nodulation of greenhouse- and field-grown kidney beans (Phaseolus vulgaris "Red Kidney") and greenhouse-grown soybeans (Glycine max "Lee"). Plants were inoculated with Rhizobium and exposed at regular intervals to simulated rain..."

"Two conditions of acidity were selected for these experiments; (a) pH 3.2 to approximate the most acidic condition commonly observed in natural precipitation, and (b) pH 6.0 to approximate the acidity that would be



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expected in precipitation formed in an atmosphere relatively free of contamination by oxides of sulfur and nitrogen.

"In all experiments, 63-93 percent (75 percent average) fewer nodules were formed on the plants exposed to 'rain' of pH 3.2 than of pH 6.0. More plants failed to form nodules when exposed to 'rain' of pH 3.2 than when exposed to pH 6.0. Overall, 74 percent of the plants which failed to form nodules had been exposed to 'rain' of pH 3.2."

"Total nodule weight of plants exposed to 'rain' of pH 3.2 was significantly lower than for those plants exposed to 'rain' of pH 6.0. No significant differences were detected in average weight of individual nodules formed on the plants exposed to the two 'rain' conditions. Therefore, acidified 'rain' appeared to have a greater effect on formation of nodules than it did on development of nodules once they were initiated."

"No consistent differences were observed in fresh weight of shoots, roots or pods. This was true in both the field and the greenhouse. No important effects of acid 'rain' were detected in number of pods formed, in soil acidity, or in the amounts of essential elements in the soil or foliage of the plants after 17 weeks of intermittent field exposures to 'rain' of pH 3.2 and pH 6.0."....

"The results presented here represent the effects of an important component of acid rain (sulfuric acid), and as such, present an indication of the types of effects which might be expected from naturally occurring rains of equivalent acidity. However, the results suggest that under those circumstances of normal agricultural practice where limiting recommendations are followed to optimize crop production, ambient levels of acidic precipitation currently occurring in the eastern United States (pH 4.5-4.0) are unlikely to result in measurable effects on leguminous crop nodulation in the field....Inhibition of nodulation was partially or completely reversed in three of four soil types tested by addition of dolomitic lime (0.75 g/kg soil—1500 kg/ha)..."

"In conclusion, the results of these experiments indicate that while temperate crop legume nodulation can be significantly impacted in unlimed soils of low buffer capacity, normal agricultural practice should preclude negative effects in crop systems under exposure regimes in the eastern United States. Natural ecosystems in which leguminous species are major components appear to represent potentially sensitive targets of acid rain, however, especially on marginal sites, where soils are sensitive to acidification and should be further investigated."



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Sprugel, D. G., J. E. Miller, R. N. Muller, H. J. Smith and P. B. Xerikos. "Sulfur Dioxide Effects on Yield and Seed Quality in Field-Grown Soybeans," Phytopathology, Vol. 70, No. 12, 1980. 1129-1133.

"Field plots of soybeans were periodically exposed to elevated levels of sulfur dioxide (mean concentrations ranging from 0.09 to 0.79 ppm during fumigation) with an open-air fumigation system which minimized disruption of the normal crop environment. Although visible injury was observed in only two plots, yield at harvest was reduced in every fumigated plot compared to nearby unfumigated control plots. These yield decreases ranged from 5% to 48% and were somewhat greater than might have been expected from previous studies. Yield reductions seemed to be due to decreases in both the mean weight per seed and the number of seeds per plant. Harvest ratio (the ratio of bean weight to chaff weight at harvest) also was reduced in the more heavily fumigated plots. Seed quality was affected less than seed yield, although at the higher exposure levels protein content decreased slightly and concentrations of some mineral elements were altered."

Taylor, O. Clifton. "Effects of Air Pollutants on Citrus, "Effects of Air Pollution on Farm Commodities. Proceedings of the Symposium, Feb. 18, 1982. Izaak Walton League of America. Arlington, Virginia. 33-41.

The author assesses the impact of atmospheric concentrations of ozone, sulfur dioxide, and fluoride on citrus quality and yields. Data from various field experiments are used. He concludes that reliable dose-response functions are not yet available, but the trend of the evidence shows injury to citrus trees and fruit and lessening of yield from air pollutants. In the Los Angeles Basin, ozone has been responsible for 30 to 50 percent crop loss in lemons and oranges.

Temple, Patrick J., O. Clifton Taylor, Larry A. Benoit, Chris A. Reagan, Robert W. Lennox. "Smog Damage to Cotton in the San Joaquin Valley," California Agriculture, September-October 1983. 4-5.

"The results of this two-year study on the response of field-grown cotton to ozone indicate that cotton production in the San Joaquin Valley may be reduced up to 15 to 20 percent each year as a result of prevailing ozone concentrations, soil moisture, and by climatic conditions that may suppress or enhance the ozone effects."

"The greater susceptibility of SJ-2 cotton to ozone in 1982 was attributed to the cooler, more humid growing conditions. Under high evaporative demand, as during the summer of 1981, plants can wilt rapidly in late morning or early afternoon; stomates (pores in leaves through which plants exchange gases with the air) close and gas exchange is reduced. In 1982,



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evaporative demand was lower; plants rarely wilted, and stomates remained open all day. More ozone could enter leaves during mid-or-late afternoon when ozone levels were highest, as compared with 1981 conditions, when stomates may have been closed. Thus, despite much lower ozone concentrations in 1982, yield reductions in the two years were comparable. Ozone-added treatments began several weeks earlier in 1982 than in 1981, during boll initiation and early development; this may have contributed to the large yield reductions at the highest ozone concentrations in 1982."

Thompson, C. Ray. "Effects of Air Pollutants on Forages," Effects of Air Pollution on Farm Commodities. Proceedings of the Symposium, February 18, 1982. Izaak Walton League of America, Arlington, Virginia. 43-55.

The author assesses the impact of atmospheric concentrations of ozone, oxides of nitrogen, and sulfur dioxide on alfalfa and forage grasses. Data from various field experiments are employed. He concludes that different varieties show differing levels of tolerance to air pollutants, and that some varieties show significant reduction in forage yield at specified levels of pollutant exposure.

Thompson, C. R., Gerrit Kats, and J. W. Cameron. "Effects of Ambient Photochemical Air Pollutants on Growth, Yield, and Ear Characteristics of Two Sweet Corn Hybrids," Journal of Environmental Quality, Vol. 5, No. 4, 1976. 410-411.

"Two sweet corn hybrids (Bonanza and Monarch Advance) were evaluated for their relative susceptibility to ambient photochemical air pollutants (principally ozone) in outdoor chambers. The plants were exposed daily to ambient or activated carbon filtered air, from seedling emergence to fresh market harvest. Plant height, tiller number and length, and air dry weight of stalks were reduced by pollutants in both cultivars. The number and fresh weight of marketable primary ears and the number of fully developed kernels were much severly reduced in Monarch Advance. Some acute leaf tissue collapse and premature yellowing and senescence of leaves were prominent in Monarch Advance but nearly absent in Bonanza. These foliar symptoms agree with previous data on the behavior of the two cultivars in the field."

Tingey, David T. and Richard A. Reinert. "The Effect of Ozone and Sulphur Dioxide Singly and in Combination on Plant Growth," Environmental Pollution, Vol. 9, 1975. 115-125.

Plants were exposed to ozone ($O_3$) and sulphur dioxide ($SO_2$) singly or in combination to examine the effects of gas mixtures on plant growth. In the



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chronic exposures of alfalfa (Medicago sativus) and tobacco (Nicotiana tabacum) the experimental procedure consisted of the following treatments: 0.05 ppm $O_3$, 0.05 ppm $SO_2$, a mixture of the two gases at these concentrations, and an unfumigated control chamber. Groups of radishes (Raphanus sativus) received the following individual treatments: 0.15 ppm $O_3$; 0.45 ppm $SO_2$; 0.15 ppm $O_3$ with 0.45 ppm $SO_2$; 0.45 ppm $O_3$ with 0.45 ppm $SO_2$; and charcoal filtered air. Chronic exposure of tobacco to these mixtures resulted in growth reductions from the mix treatment equal to the additive effect of the single gases. "Chronic exposure of alfalfa resulted in growth reductions from the mixed treatment that were less than the additive effects of the single gases. Single acute exposures of radish to $O_3$ and/or $SO_2$ resulted in growth reductions in the mix treatment no different from the effects of individual gases. None of the gas mixtures caused a greater growth reduction than would be expected from the additive effects of the single gases. This is in contrast with foliar injury, where gas mixtures frequently cause more foliar injury than the sum of the individual pollutants."

Tingey, David T., Richard A. Reinert, John Dunning, and Walter W. Heck. "Vegetation Injury from the Interaction of Nitrogen Dioxide and Sulfur Dioxide," Phytopathology, Vol. 61, No. 12, December 1971. 1506-1511.

"Six plant species [tobacco, pinto bean, tomato, radish, oats and soybean] were exposed for 4 hr to nitrogen dioxide and/or sulfur dioxide in greenhouse exposure chambers. Although concentrations of $NO_2$ below 200 pphm and concentrations of $SO_2$ below 50 pphm caused no leaf injury, injury did develop when plants were exposed to mixtures of 5 to 25 pphm of each of the two gases. Leaf injury from either $NO_2$ or $SO_2$ alone occurred as marginal and/or interveinal necrosis on each leaf surface (bifacial). Injury produced by a mixture of the two gases appeared as chlorotic and necrotic flecking on the upper surface of the interveinal areas of tomato, radish, oats and tobacco. Reddish-brown lesions (stipple) developed on pinto bean and soybean leaves. Lower surface injury frequently occurred in the mixed-gas fumigations, with little or no upper surface injury. The concentrations on $NO_2$ + $SO_2$ which caused plant injury were similar to those found in urban areas, and may result in yield losses for plants under field conditions."

Tingey, David T., Richard A. Reinert, Carlos Wickliff, and Walter W. Heck. "Chronic Ozone or Sulfur Dioxide Exposures, or Both, Affect the Early Vegetative Growth of Soybean," Canadian Journal of Plant Science, Vol. 53, October 1973. 875-879.

"Soybean (Glycine max (L.) Merr.) cultivars Hood and Dare were exposed to low concentrations of ozone or sulfur dioxide, or both, during the first 3 weeks of growth. Foliar injury occurred on both cultivars in the ozone and



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mix treatments. Dare developed more foliar injury than Hood. Plant height, top and root flesh and dry weights, and the dry shoot-root ratios were significantly reduced by the 10-pphm ozone treatment. The mix of 5 pphm ozone plus 5 pphm sulfur dioxide significantly reduced top fresh weight, root fresh and dry weights, and shoot-root ratios. Treatments of 5 pphm ozone, 5 pphm or 20 pphm sulfur dioxide had no significant effects on plant growth. The growth reductions resulting from the ozone-sulfur dioxide mix were greater than the additive reductions of the single gases. The lack of a significant cultivar-treatment interaction indicated that the growth of the cultivars responded similarly to the various treatments."

Troiano, John, Luke Colavito, Larry Heller, and Dale McCune. "Effects of Simulated Acid and Photochemical Oxidant on Seed Development in Soybean," Phytopathology, Vol. 71, No. 5, 1981. 565.

"Two cultivars of soybean (Glycine max cv Williams and Beeson) were exposed to acidic rain and photochemical oxidant in a 3x2 factorial design: simulated rain at pH 4.0, pH 3.4, and 2.8 applied in covered field chambers receiving either filtered or unfiltered air. After harvest plants were air dried to retain seed viability. In Williams the percent germination of seed at pH 4.0 was greater than pH 2.8 and a maximum occurred at pH 3.4. At each level of acidity seed from plants grown in filtered air had a greater percent germination than from unfiltered air. Among treatments, germination was negatively correlated with occurrance of green seed but not correlated with seed size. In Beeson, there was no consistent treatment effect on germination with green seed or seed size. These results indicate that pollutant stress may alter the developmental relationships between vegetative and reproductive organs."

Walker, Jerry T. Characterization of Rain in the Georgia Piedmont and Effects of Acidified Water on Crop and Ornamental Plants. Research Bulletin 283, November 1982. College of Agriculture, Experiment Stations, Athens, Georgia.

"Plant species and cultivars varied in susceptibility to injury by sulfuric acid mists applied to leaves. No detectable injury occurred on any greenhouse or growth chamber plants misted with low volume solutions adjusted to pH values 2.6, 3.0, 4.0, and 6 regardless of the number of applications. Solutions at pH of 1.8 and 2.2 did cause slight to moderate injury in the form of localized white leaf lesions on the abaxial leaf surfaces. Injury generally was seen within 48 hours following treatment, and was more intense with pH 1.8 treatments than with 2.2 treatments..." [Plants studied in this experiment were: alfalfa, bean, clover, cucumber, geranium, marigold, peanut, petunia, radish, salvia, snapdragon, soybean, sweetcorn, tobacco, and zinnia.]

[In another experiment]..."The unfavorable environmental conditions (drought) in experimental field plots in 1980 precluded obtaining meaningful data on



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biomass production. The mean fresh weight for bean, tomato, radish, and soybean, and bean fruit weight and number of tomato fruit per plant were greater as a result of pH 2.6 treatment than with other treatments * in 1981. However, soybean was the only plant with significantly greater yield than the controls at this pH...."

[*Treatments were applications of mist of pH values of 1.8, 2.2, and 2.6. Yields of plants misted at pH 2.6 exceeded yields of the control plants, which were not misted at all, although as noted, only the soybean yield advantage for pH 2.6 mist over control was statistically significant.]

Nitrate and sulfate are the greatest ionic components of precipitation. Contrasted with data from other locations in the U.S. (Ohio, for example, which has 3 times greater $SO_x$ emissions), this is approximately 42 and 38% less for nitrate and sulfate. Nevertheless, it must be considered that the constituents of precipitation do contribute something to the nutrient status of soils, lakes, and streams in the piedmont and to the Southwest..."

"The average ozone concentrations for the growing seasons of 1979, 1980, and 1981 are 3.02, 4.13, and 3.67 parts per hundred million (pphm), respectively (60.4, 82.6, and 73.4 microg/$m^3$). We have monitored ozone levels at this location almost every year since 1973 and have increased the monitoring time considerably each year. The yearly daily average oxidant readings for these periods have ranged from 2.12 pphm in 1973 to 5.23 in 1978. The highest daily averages for 1979, 1980, and 1981 occurred in July or August when more than 10 pphm was recorded for 2.5 hr. on August 15, 1979. A level of 9.8 pphm was noted on July 17, 1980, for 1 hr. 40 min, and on August 24, 1981, a level of 8.8 pphm..."

"The concentrations present in rural Georgia have not, as yet, attained the sustained high concentrations noted in areas such as the West Coast or northeastern U.S...."

Weinstein, L. H., D. C. McCune, A. L. Aluisio and P. Van Leuken. "The Effect of Sulfur Dioxide on the Incidence and Severity of Bean Rust and Early Blight Tomato," Environmental Pollution, Vol. 9, 1975. 145-155.

"The effects of relatively low concentrations of $SO_2$ (less than 20 pphm) on the incidence of bean rust and early blight of tomato were studied. Pinto beans (Phaseolus vulgaris L. cv. 'Pinto') and tomato (Lycopersicon esculentum Mill. cv. 'Bonny Best') plants were used in these investigations. Plants were exposed to charcoal filtered air or to $SO_2$ in controlled-environment fumigation chambers. Sulfur dioxide affected bean rust but not early blight of tomato under the conditions used in these experiments. The effect of $SO_2$ on bean rust consisted of a decrease in the incidence and severity of the disease and in the size and percentage germination of uredospores. These effects resulted from exposure of plants to $SO_2$ before or after



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inoculation with the pathogen, but exposures before inoculation were more effective. The different responses of the two diseases to $SO_2$ could reflect a difference between the pathogens in their tolerance to $SO_2$. However, the results speak more for an indirect than for a direct effect on the pathogen; one which involves an $SO_2$ induced change in the resistance of the host and in its suitability as a habitat for the pathogen."

Wood, T. and F. H. Bormann. "Increases in Foliar Leaching Caused by Acidification of an Artificial Mist," Ambio, Vol. 4, 1975. 169-173.

"1) This study was undertaken to investigate the effects of acidified rain on the foliar leaching of nutrient cations from pinto bean and sugar maple seedlings."

"2) Increases in foliar losses of (potassium, magnesium, and calcium ions) from both species were associated with increases in the acidity of an artificial mist."

"3) At pH's of 3.0 and below, tissue damage, presumably caused by high concentrations of hydrogen ions, may have contributed greatly to the increased cation losses found at these levels."

"4) At pH's of 3.3 and above, although no tissue damage was observed, increases in the foliar leaching of (potassium, magnesium and calcium ions) from pinto beans were found. Sugar maple lost more calcium ions at pH 3.3 than at pH's 4.0 and 5.0, but losses of potassium ions and magnesium ions were not affected at these acidity levels."

"5) Despite the absence of statistically significant hydrogen ion uptake by the leaves, increased cation losses in the absence of visible tissue damage are evidence in support of a) hydrogen ion exchange as a mechanism for foliar leaching, and b) the hypothesis that increased rainwater acidity, regardless of the mechanism, may be accelerating foliar leaching of nutrient cations from exposed plants."

"6) A comparison of our experimental leaching rates with natural losses observed under a hardwood canopy indicates difficulties in quantitatively translating laboratory results to field conditions. However, we feel that the observed increases may be of importance in qualitative considerations of nutrient cycling in forest and agricultural ecosystems, since precipitation with pH's of 4.0 and less have been falling on Northern Europe and the Northeastern U.S. for at least the past two decades."



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Woodmansee, Robert G. "Sulfur in Grassland Ecosystems," Sulfur in the Environment. Report of the Missouri Botanical Garden, St. Louis, Missouri, April 1975. Revised July 1975. 134-140.

When grassland ecosystems are impacted by sulfur emissions from urban sources or rural electric plants, effects will result either (1) "through direct, toxic disruption of the metabolism of organisms and consequent reduction in productivity, or" (2) "through more subtle indirect influences favoring shifts in species composition within the ecosystem as a result of the alteration of the environment."

Indirect influences would be sublethal effects upon plants or animals which reduce their competitive ability. Sublethal influences upon species composition might be changes in soil characteristics such as pH, dominant ions in salts, and change in cycling rates of sulfur or other necessary nutrients. However, there are very few field studies which actually assess these potential effects.



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## Economic Effects on Crop Producers and Consumers

Adams, Richard M. and Thomas D. Crocker. "Economically Relevant Response Estimation and the Value of Information: Acid Deposition," Economic Perspectives on Acid Deposition Control. Ed. Thomas D. Crocker. Vol. 8 in the Acid Precipitation Series, John I. Teasley, Series Ed., Butterworth Publishers, Boston, 1984. 35-64.

"Dose-Response Information: An Empirical Example... Agricultural Problem...
"[B]ecause of the readily available economic and dose response data bases for agriculture, it will serve as the empirical example of ecosystem response used here. The pollutant of interest in this volume is acid deposition. As noted earlier, with the exception of... soybeans, there is little in the way of acid-deposition agricultural crop response information... This situation is in sharp contrast to current information on oxidants, where research on plant effects dates back at least three decades... Inquires of this type are being directed by [the] National Crop Loss Assessment Network (NCLAN), a coordinated research program whose objectives include an economic assessment of oxidant damage to major agricultural crops. Response information for selected crops drawn from NCLAN data will be used as a surrogate for acid deposition to implement the above valuation approach..."

Based upon estimates of demand and supply relationships for corn, soybeans, and cotton, and ozone dose-response functions for those crops, the authors estimate the national economic surplus accruing to producers and consumers of those crops under four alternative levels of ozone to which each crop is assumed to be exposed: 1) No oxidant standard, assumed to equal 0.18 ppm ozone peak for a seven-hour average exposure during the growing season; 2) the current ozidant peak standard of 0.12 ppm; 3) an improved air quality peak standard of 0.10 ppm; and 4) an even more improved or restrictive peak standard of 0.08 ppm.

Hypothetical exposure of these crops at the current standard of 0.12 would lead to an economic surplus $3.4 billion larger than under an exposure of 0.18 (no standard); exposure of the crops at 0.10 leads to a surplus $1.1 billion larger than at 0.12; and exposure at 0.08 (the best air quality studied) leads to a surplus also $1.1 billion larger than at 0.10. Therefore, adding each of these amounts (all in 1979 dollars), the economic surplus from these crops under the least-ozone/cleanest air alternative is $5.5 billion greater (after rounding) than under the most-ozone/dirtiest air alternative. The authors go on to illustrate their method of estimating how valuable this kind of information would be to decisionmakers who need to decide which oxidant standard to select.



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Adams, R. M., T. D. Crocker, and N. Thanavibulchai. "An Economic Assessment of Air Pollution Damages to Selected Annual Crops in Southern California," Journal of Environmental Economics and Management, Vol. 9, No. 1, 1982. 42-58.

"Agricultural production is influenced by many factors beyond the control of individual producers. In recent decades, air pollution has become one of these exogenous factors. This study uses a price-endogenous mathematical programming model to assess the economic benefits of reducing 1976 ambient oxidant exposures of 14 annual crops in southern California. A measure of the distributional consequences of these benefits across producers, consumers and locations is also provided. Results indicate that 1976 benefits of air pollution control for the 14 included crops would have been approximately $46 million."

Adams, Richard M., Scott A. Hamilton, and Bruce McCarl. The Economic Effects of Ozone on Agriculture. EPA Report 600/3-84-090. Environmental Research Laboratory, Office of Research and Development, U. S. Environmental Protection Agency, Corvallis, Oregon, September 1984.

"This manuscript is a report of an assessment of the economic consequences of ozone pollution on U. S. agriculture. The economic analysis is limited to those ozone effects directly associated with the production and consumption of a set of agricultural commodities. Effects on non-agricultural commodities as well as compliance costs of achieving any changes in ambient ozone levels are not evaluated here, hence the estimates are not net economic effects. The assessment is based on a large scale spatial equilibrium model of the U. S. agricultural sector. The ozone analyses are driven by ozone-yield response functions derived from four years of NCLAN data. The assessment covers the major annual crops * in the U. S. and traces these crop yield effects through the livestock sector to final consumption, both domestic and foreign."....

[* Corn, soybeans, wheat, cotton, grain sorghum, and barley. The response of hay to ozone is also estimated by a simpler method. A livestock production and feeding module expresses the derived demand for feed grains after the impact of ozone on grain yields is estimated.]

"The economic model was validated by comparison with actual performance of the agriculture sector in 1980. Following the establishment of a credible base model, the model was perturbed according to the yield adjustments predicted in each of the ozone analyses. The resultant economic estimates indicate that benefits of reduced ozone will accrue to both agricultural producers and consumers. Specifically, a 25 percent change in ozone below current ambient levels results in a benefit to society of from $1.6 to $1.9 billion, depending on the underlying response assumption. Conversely, a 25% increase in ozone produces a cost (negative



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benefit) to society of $1.9 to $2.3 billion. Ozone alterations of 10 percent and 40 percent show lower or greater benefits, as expected." [In addition, the authors list six improvements which could be accomplished in the future to improve, extend, clarify, or test the sensitivity of their analyses.]

Benedict, H. M., C. J. Miller, and R. E. Olson. Economic Impact of Air Pollutants on Plants in the United States. Final report prepared for Coordinating Research Council, New York, N. Y. by Stanford Research Institute, Menlo Park, California. November 1971.

In essence, the formula used by this report to estimate the approximate dollar loss of a certain crop because of air pollution is: Dollar loss equals the value of the crop times the percentage reduction in the crop yield attributable to air pollution. Crop value is thus determined by crop quantity (before and after pollution) times invariant price, that is, price which does not change between the "before" and "after" pollution situations.

"...551 of the 3,134 counties in the United States were selected as having potential plant-damaging exposure to oxidants, sulfur dioxide and fluorides. Of these, 327 would be exposed to oxidants, 336 to sulfur dioxide, and 86 to fluorides. (Some counties would be exposed to two or more.) On the basis of area and population in these counties, it was estimated that about 9% of the area and 62% of the population occurred in counties likely to have plant-damaging oxidant pollution. The respective values were 13% and 54% for sulfur dioxide and 4% and 9% for fluorides. It was further calculated that 27% of the dollar value of crops grown in the United States occurred in the 551 pollution-threatened counties. The highest percentages were found in the Middle Atlantic States and the lowest in the West North Central States."

"Based on estimates of losses found to occur to various crops and ornamentals in the most severely polluted counties, tables were prepared showing the factors to be applied to values of crops and ornamentals grown in the different classes of counties. This procedure gave the estimated loss to a specific crop in the various counties due to oxidants, sulfur dioxide or fluorides."

The report estimates that for all the polluted areas studied in the United States, the total crop loss attributable to air pollution in 1964 was $131.9 million. Crops studied were field crops, seed crops, fruits and nuts, vegetables, forest and nursery crops, citrus, and ornamentals. Of the total estimated loss, $121.4 million was caused by oxidants, $6.2 million by sulfur dioxide, and $4.3 million by fluorides. Of the $131.9 million total, the largest regional amount--$50.2 million--occurred in the Pacific region, with the next largest amount--$26.8 million--in the South Atlantic region. [See Table 17 of the report.]



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Benson, F. J., S. V. Krupa, P. S. Teng, and D. E. Welsch. Economic Assessment of Air Pollution Damage to Agricultural and Silvicultural Crops in Minnesota, prepared for Minnesota Pollution Control Agency, Roseville, Minnesota, March 1982.

This study contains two parts. The first part estimates 1979 and 1980 yield losses due to ozone for alfalfa, corn, wheat, and potatoes in Minnesota. The study estimates that, in 1979, ozone concentrations caused crop losses in total quantity produced as follows: Alfalfa, 0.5 percent loss in production, statewide; corn, wheat and potatoes, no loss. In 1980, estimated losses were: Alfalfa, 7.3 percent; corn, 0.3 percent; wheat, 1.1 percent; potatoes, no loss. However, error margins associated with these estimates are substantial.

The losses due to ozone appear to be generally comparable to losses from biological damage agents -- insects, weeds, and other pests. In counties of Minnesota where ozone concentrations were higher, crop loss percentages were higher. Therefore, the above estimates are statewide averages, covering areas showing light, moderate, or heavy ozone concentration, as well as rare, occasional, or frequent occurrence of these concentrations.

With respect to commercially valuable trees, the study does not go beyond literature review.

The second part of the study is economic, and uses alternative assumptions about ozone concentration and frequency to operate crop loss models, obtaining alternative physical loss estimates. Under alternative price assumptions, these physical losses are then converted to alternative estimates of the annual dollar value of the losses of these four crops in Minnesota. The discounted present value of losses for a 15-year period is also calculated for these crops.

If crop losses were confined to Minnesota alone (assuming ozone pollution only in that State) crop prices would be relatively stable because crop supplies would be ample. Then, under that assumption, as ozone concentration and frequency increase, losses increase and the total value of production declines compared to a situation of no crop loss.

However, if crop losses were to occur over the entire U.S. at the same rates as in Minnesota, crop prices would rise because of shorter supplies nationally. Then, under that assumption, as ozone concentrations and frequency increase, losses increase; but, the total value of production could increase compared to a situation of no crop loss. This is because crop prices would rise, since the economic demand for the commodities in this study is price-inelastic.



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Brown, Deborah J. and Jim Pheasant. An Assessment of Economic Damages from Ozone to a Set of Representative Midwest Farms. Station Bulletin No. 435, Agricultural Experiment Station, Purdue University, West Lafayette, Indiana. October 1983.

"Soybeans are considerably more sensitive to ozone than wheat and corn. Farmers faced with differential yield improvements should, therefore, theoretically shift their acreage between these crops as ozone levels change. Previous studies....of economic benefits or losses from changes in ozone levels have not considered this acreage substitution in response to differential yield changes. Failure to consider such substitution, however, could cause misestimation of the benefits from air pollution control legislation because limiting farmers to their current cropping patterns would tend to cause an underestimate of the benefits from ozone reduction, and an overestimate of the losses from ozone increases."

"This study uses the Purdue crop budget linear programming model (REPFARM) to model a set of farms for sixteen corn belt regions (4 in Iowa, 3 in Ohio, 3 in Illinois, 2 in Indiana, and 4 in Missouri). At this representative farm level, substitution between crops and the resulting farm income changes in response to yield changes can be clearly observed."

"Estimates of crop yield changes for six ozone levels in these sixteen regions were provided by the National Crop Loss Assessment Network (NCLAN). These ozone levels included a base case (reflecting current environmental and economic conditions), two cases where ozone is reduced (one to a background level of 35 ppb and one to a 45 ppb level), and three cases where ozone increased (to 55, 65, and 75 ppb)."

"Crops grown vary from region to region. Holding prices constant (at $2.25/corn, $3.15/wheat) the shift from corn to soybeans [acreage] as ozone levels fall is quite significant... An average base soybean acreage across the sixteen farms of 309.9 acres (including single crop, double with wheat, and rotation beans with corn) declines to 187.1 acres as ozone is increased to 75 ppb, and increases to 386.7 acres as ozone is reduced to background levels. Income (net variable, but not fixed, costs) follows the same pattern as soybean acreages--dropping by an average over the sixteen farms of 10.4% as ozone rises from the base level to 75 ppb, and rising by an average of 8.7% as ozone drops to background levels..."

"As acreage shifts, the relative prices of the various crops would also presumably change....[T]his report [also] gives the results of changing relative prices on the acreage mix of the 4 Iowa and 2 Indiana farms under three alternative ozone levels. In general, an increase in air quality above the current base levels associates an increasing soybean to corn price ratio with smaller shifts out of corn. Indeed beyond some soybean to corn price ratio, (2.6 in the case of Central Iowa), there is no additional decrease in corn acreage. This is partly due to the elimination of continuous corn, but the continuation of rotation corn."



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"It therefore appears that acreage shifts and therefore benefits from ozone reduction depend critically on the soybean-corn price ratio. This implies that estimates of such benefits made using representative farms should be linked to sectoral models which incorporate price changes..."

Crocker, Thomas D. "Pollution Damage to Managed Ecosystems: Economic Assessment," Effects of Air Pollution on Farm Commodities. Proceedings of the Symposium, February 18, 1982. Izaak Walton League of America, Arlington, Virginia. 103-124.

The author discusses methods for assessing economic damage to agriculture from air pollution. He uses summary data on air pollution damage to the following crops in California: Selected fruits and vegetables, cotton, and sugar beets. Two alternative methods of analysis are proposed: (1) Mathematical (quadratic) programming and (2) dual cost functions, both methods already established in economics. The author argues that complete assessment of economic consequences for agriculture of air pollution must consider economic adaptations of farm producers to pollution as well as market price responses.

Crocker, T. D. and B. A. Forster. "Decision Problems in the Control of Acid Precipitation: Nonconvexities and Irreversibilities," Journal of the Air Pollution Control Association, Vol. 31, No. 1, January 1981. 31-37.

The economic justification of controlling the effects of acid precipitation partly depends on the degree of an ecosystem's current and potential injury from acidity. The intermediate level of harm to a variety of ecosystems now permitted may be the least desirable policy, according to economic criteria. Unless control measures achieve a sufficiently high level of effort to prevent a slide into irreversible environmental damage, control efforts may show low benefit-cost ratios. Natural science, economic research, and public policy should concentrate first on those systems that are on the verge of acidification.

Heck, Walter W., Richard M. Adams, William W. Cure, Allen S. Heagle, Howard E. Heggestad, Robert J. Kohut, Lance W. Kress, John O. Rawlings, and O. Clifton Taylor. "A Reassessment of Crop Loss from Ozone," Environmental Science and Technology, Vol. 17, No. 12, December 1983. 572A-581A.

"Two steps were used to calculate economic effects. First, physical adjustments or changes in regional production were predicted for three agricultural commodities (corn, soybean, wheat) under three alternative ozone doses using NCLAN data and the linear and Weibull [dose-response



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functions] * discussed earlier. Second, these regional production losses were then used to drive the economic model, which provides estimates of the direction and magnitude of economic benefits or losses associated with the alternative $O_3$ levels."....  [ * The Weibull dose-response function is nonlinear.]

"The economic framework used here addresses some, but not all, economically important issues associated with $O_3$ pollution. Specifically, the economic model predicts price adjustments that may arise with changes in crop production due to $O_3$ and estimates the effect of such price changes on consumer and producer well-being."....

"Using $O_3$ data for the 13 subregions in the corn belt and the linear and Weibull [dose-response functions], potential changes in crop production associated with varying $O_3$ levels were calculated. The average production (for each crop) for the period 1978-80 was used as the base level..."

"The economic benefits incease as $O_3$ concentrations decline. At a concentration of 0.04 ppm, the benefits of an $O_3$ reduction below 1980 ambient levels for these three corn belt commodities are $0.73 billion with the linear [functions] and $1.19 billion with the Weibull [function] (5-8% of the corn belt gross value of farm commodities). The 0.05 ppm concentration is relatively close to ambient for most regions and results in a benefit of approximately $0.14 billion with the linear and $0.23 billion with the Weibull [function]. For these $O_3$ levels, the use of the Weibull [function] results in substantially greater estimates of the benefits of control than the linear [function]."

"However, the opposite case is noted for the 0.08 ppm analysis. Here, total economic surplus is reduced by $3.13 billion according to the linear [function] and $2.99 billion with the Weibull (approximately 20% of the corn belt values). This reversal in relative effects in the linear case arises primarily from corn, which, in keeping with the linear-plateau model, is insensitive to $O_3$ at current ambient or lower levels but is moderately sensitive at higher $O_3$ concentrations..."

"The results of this type of economic assessment need to be placed in perspective. Besides being unable to account for adjustments in regions outside the corn belt, it should be noted that this economic assessment is unable to account for adjustments the producer makes to compensate for losses, such as substitution of cultivars or crops, locational adjustments, and management strategies that may reduce or increase economic losses, depending on the direction of movement in air quality. Such adjustments are included in the forthcoming NCLAN national economic assessment, which uses a method that incorporates mathematical programming. In this, as well as in most other economic procedures, the effects on yield obtained with response models serve to start the economic mechanisms in motion. The ultimate economic effect of these alterations in crop yield may be less apparent than the triggering yield changes, as the economic losses or benefits may not parallel these changes."



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Heck, W. W., W. W. Cure, D. S. Shriner, R. J. Olson, and A. S. Heagle. "Ozone Impacts on the Productivity of Selected Crops," Effects of Air Pollution on Farm Commodities. Proceedings of the Symposium, February 18, 1982. Izaak Walton League of America, Arlington, Virginia. 147-176.

The authors assess potential gain in value of production of soybeans, corn, wheat, and peanuts if current ozone levels were substantially reduced. They employ data from the National Crop Loss Assessment Network, the 1978 Census of Agriculture, EPA air quality monitoring, and individual field and greenhouse experiments. They use simple linear regression to (1) estimate percent yield reduction as a function of ozone dose and (2) apply that yield reduction, that is, a potential yield loss, in order to estimate potential gain foregone in 1978 for the listed commodities. 1978 crop prices are assumed. There is no attempt to account for price effects attributable to a potentially larger crop if ozone concentration were lessened. Based on actual 1978 prices assumed for this model, a reduction in ozone to below 25 ppb would have resulted in $3 billion additional value in production: Soybeans ($2 billion additional), corn ($517 million more), wheat ($375 million additional), and peanuts ($218 million more).

Howitt, Richard E., Thomas W. Gossard, and Richard M. Adams. "Effects of Alternative Ozone Concentrations and Response Data on Economic Assessments: The Case of California Crops," Journal of the Air Pollution Control Association, Vol. 34, No. 11, November 1984. 1122-1127.

"The economic impact of various ozone concentrations on California agriculture is examined using an economic model of crop production that accounts for interdependence among crops. Such interdependence recognizes that net economic effects are determined not only by yield sensitivity to ozone but also by market conditions that affect relative crop prices and [illegible]ability. Changes in crop yields due to alternations in ambient ozone concentrations are used to drive the economic model. The predicted yield changes are derived from NCLAN data under a range of assumptions concerning functional form and yield effects. The results indicate that the economic effects of ozone are substantial for 13 included crops."....

"The California Agricultural Resources Model (CARM) used in this study.... [includes] 38 crops and 14 regions....CARM is a nonlinear programming model that assumes farmers act so as to maximize their farm profit, subject to land, water, air quality and other agronomic constraints."....
[Of the 38 crops, 13 are judged sensitive to ozone. These are: Alfalfa, dry beans, corn, cotton, grain sorghum, lettuce, tomatoes, wheat, barley, celery, onions, potatoes, and rice.]

"The percent changes in total economic surplus are less than the initial yield changes used in each ozone analysis, indicating the mitigating nature of the economic processes of acreage substitution captured in the economic model. The magnitude of these benefit estimates are consistent



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with those reported elsewhere for a more restricted set of crops in California and larger changes in average ozone concentration. Thus, impact analyses that address only the producer's gains (or losses) and ignore shifts between crops significantly understate the impacts of deterioration in the ambient ozone level."

[Model results are reported as differences in producers' and consumers' surplus from that surplus associated with 1978 ambient ozone levels.] "In general, as air quality improves, total production increases, price decreases, and acreage decreases, while increasing ozone concentration tends to decrease production, increase price, and increase acreage.... That acreages increase under poor air quality and decrease when quality is improved may be initially counterintuitive. However, the model is following the rational economic process of substituting land and other inputs for air quality....Thus, reduction in air quality further exacerbates the pressure on scarce land and water resources within California."....

[Given that 1978 ambient ozone levels lay between .04 and .08 ppm in California...] "The benefits and costs to producers under the .04 and .08 ppm scenarios represent substantial changes in profitability: +2.3% and -10.9%, respectively, for the 13 affected crops. Consumers of the affected crops would notice gains of +0.9% and losses of -3.3% under, respectively, the .04 ppm and .08 ppm ozone levels."

"[F]or both consumers and producers, the effects of ozone concentration on agriculture are substantial for the 13 included crops. While producers bear the brunt of the effects, any analysis that does not calculate ensuing price changes to consumers will be distorted....[D]ue to the interaction of price and cost effects, the change in acreage, output, or benefits cannot be reduced to a simple relationship over a range of crops. Any analysis of economic effects must account for the substitution of other inputs, such as scarce land and water resources, for deteriorating air quality."

Kopp, Raymond J., William J. Vaughan, and Michael Hazilla. Agricultural Sector Benefits Analysis for Ozone: Methods Evaluation and Demonstration. EPA Report 450/5-84-003. U. S. Environmental Protection Agency, Research Triangle Park, North Carolina, 1984.

This report was prepared for EPA under contract by the authors, economists at Resources for the Future, Washington, D. C., to assist EPA in planning a regulatory impact analysis pursuant to a possible reconsideraton of the current National Ambient Air Quality Standard (NAAQS) for ozone.

"This report has described an economic assessment model capable of estimating the welfare gains or losses emanating from the agricultural production sector in response to changes in rural ozone concentrations. The assessment model is comprised of four major components which may be improved to lead to more reliable welfare estimates. These components are:



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1) The biological information contained in the dose-response functions, 2) the air quality data supplied by EPA for both baseline and alternative exposure scenarios, 3) the economic information on agricultural cost and production contained in the RMF [Regional Model Farm], and 4) crop-specific demand functions."....

The assessment model estimates the impact on welfare (combined producers' and consumers' surplus) of exposing soybeans, corn, wheat, grain sorghum, barley, cotton and peanuts in key growing regions to different levels of ozone. The methodology preferred by the authors uses the nonlinear dose-response functions derived from field experiments by the National Crop Loss Assessment Network (NCLAN).

The first step toward calculating welfare impacts is to estimate actual 1978 average ambient ozone levels (7-hr per day seasonal means) for seven U. S. regions in which the above crops are grown (7 crops, but 3 sub-regions for soybeans). These regional averages tend to cluster around .055 ppm ozone, but obviously differ from region to region, because for each crop the growing region boundaries are different. Then, for each crop it is postulated that ozone levels change from their different ambient starting points to uniform average levels for each crop and region as specified--levels both above and below 1978 ambient, representing both improvement and degradation in ozone concentration. The change is presumed to come about through either tightening or relaxing National Ambient Air Quality Standards.

Under the above assumptions, and using the nonlinear functions, the authors estimate the following aggregate impacts of ozone changes on welfare:

| Ozone concen. ppm. | Net changes in producers' + consumers' surplus for listed crops: Soyb.NE | Soyb.SW | Soyb.Cen. | Corn | Wheat | G.Sorg. | Barl. | Cotton | P'nut. |
|---|---|---|---|---|---|---|---|---|---|
| | Million 1978 dollars | | | | | | | | |
| .03 | + 9 | +340 | +307 | +158 | +308 | + 44 | + 2 | +411 | + 68 |
| .08 | - 14 | -249 | -673 | -594 | -927 | - 82 | - 16 | -599 | -127 |

In addition, the authors conduct several sensitivity studies to determine how sensitive the welfare estimates are to various features of the assessment methodology. They conclude that the estimates of welfare gains or losses are very sensitive to whether or not the assessment model "allows" farmers to switch their planted acreage among crops or crop varieties (either to or away from those more sensitive to ozone). Thus, if the economic modeler were to exclude the possibility of crop/varietal switching as a mitigating response by farmers to ozone change, benefits of ozone reduction would always be understated, and losses from ozone increase always overstated. The sensitivity studies also conclude that the form of the biological dose-response function--whether linear or nonlinear--is also a major influence on the welfare estimates, but that demand elasticity values are not.



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Leung, S. K., W. Reed, and S. Geng. "Estimations of Ozone Damage to Selected Crops Grown in Southern California," Journal of the Air Pollution Control Association, Vol. 32, No. 2, February 1982. 160-164.

The purpose of this study was to illustrate and evaluate....methodologies for assessing ozone damage to selected agricultural crops, and for assessing the economic impacts of crop damage. The....study is unique in that damage functions were estimated from regional data and the data for the same crops were used in carrying out economic analyses of impacts from crop yield changes. The estimates of yield loss were ued to calculate producers' and consumers' surpluses as estimates of the direct impacts on those sectors. The impacts of crop production losses to other economic sectors were estimated by use of a regional input-output model.

The negative impact of $O_3$ on the yield of 8 or 9 * crops analyzed was documented in this study. The degree of damage varied from zero to 57 percent reduction according to the crop and location. The yield losses led to reductions of producers' and consumers' surpluses of $57.3 and $45.7 million, respectively. This direct monetary impact translates through input-output analysis to income losses of $117.5 million in the South Coast Air Basin regions."

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* - Alfalfa, avocado, lemon, lettuce, navel orange, Valencia orange, strawberry, and tomato. No yield change estimates were made for celery.

Liu, Ben-chieh and Eden Siu-hung Yu. Air Pollution Damage Functions and Regional Damage Estimates, Technomic Publishing Co., Westport, Connecticut, 1977.

In Chapter VI of their book, the authors attempt to estimate economic damage functions which relate economic losses for a variety of crops to air pollution concentration levels and climatological variables. A stepwise linear multivariate regression model was developed for determining the economic damage functions for selected crops and plants based mainly on the economic importance of these crops in the United States. Data for the regression analysis were obtained from prior studies on vegetation losses and climatological data. Economic damages for total crops, total ornamentals, and all plants were estimated for 74 counties. The authors stress that the damage functions presented, though useful for estimating possible damage reductions brought about by pollution abatement programs, should be interpreted and employed with caution. They suggest that the best way to determine the occurrence and severity of an air pollution episode is to install a network of recorders to measure the daily and hourly concentration of various pollutants and the physical effects simultaneously.



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Loehman, Edna, William Lee, Eilif Trondsen, Marilyn Bland, Richard Goen, Francis Ludwig, Thomas Eger, Steven Eigsti, Denise Conley, and Ronald Cummings. An Estimate of the Nonhealth Benefits of Meeting the Secondary National Ambient Air Quality Standards. Final report prepared for the National Commission on Air Quality by SRI International, Menlo Park, California. January 1981.

"Benefits of approximately $6.8 billion were estimated for four major categories: Materials $4.0 billion, crops $1.8 billion, soiling $0.5 billion, and visibility $0.5 billion."

The following extracts from the report refer only to the sections on crops: "The concentrations of ozone and sulfur dioxide found in nonattainment counties can cause physiological damage to vegetation. Experiments carried out under field conditions indicate that for sensitive species yields may be reduced by 50% or more. Ozone is the primary source of damage to vegetation in the United States, because levels exceeding the standard of 0.12 ppm are found in over 500 counties....We gave high priority to identifying damage functions relating ozone concentrations to vegetation damage....Damage to agricultural crops may consist of a reduction in the yield or [of] reductions in quality from blemishes or leaf injuries...."

"The equation for calculating the costs of damage to vegetation from air pollution is: Cost of damage = percent reduction in yield X production X price." Prices used were national average market prices for 1980.

"Vegetation
Our vegetation estimates are for economically important agricultural crops. We do not include benefits to timber production or ornamentals. The results can be broken down by chronic versus acute effects and by pollutant... For crops, the benefits of meeting the oxidant standard are far greater than the direct benefits of meeting sulfur dioxide standards. This finding is consistent with the relative size of the areas that are not in compliance with each standard. The number of nonattainment counties for oxidants is nearly six times the number of nonattainment counties for sulfur dioxide. In addition, the counties with high oxidant concentrations include most important agricultural areas, while those with high sulfur dioxide concentrations are characteristically more urban."

"The damage from acute doses of oxidants slightly exceeds that from chronic doses. Therefore, it is important to try to prevent episodes of very high ozone concentrations for periods of 1 to 3 days as well as persistent concentrations that exceed the standard only slightly. Such a policy is difficult to implement because episodes are largely a function of meteorological conditions....Tomatoes and corn suffer the most damage. However, for corn the damage is caused by acute doses of oxidants, while 55% of the damage to tomatoes is caused by chronic doses. Similarly, chronic doses cause the most damage to alfalfa, potatoes, broccoli, and cabbage. For soybeans, sweet corn, tobacco, and wheat, damage is about equally divided between acute and chronic doses."



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Loehman, Edna, and Tom Wilkinson. Ozone Damage to Field Crops in Indiana. Station Bulletin No. 426, Agricultural Experiment Station, Purdue University, West Lafayette, Indiana. October 1983.

"Assumptions
Economic benefits of air quality improvements are most properly defined in terms of savings to consumers and increases in income to producers. However, the most common procedure for valuing crop effects such as those described above is to use the market price times the change in crop yields to measure benefits. Use of this measure embodies several assumptions: (1) Market price is not affected by the increase in yield; (2) marginal costs of production shift to reflect a costless increase in production when yields change; (3) farmers continue planting the crops after the yield change as before."....

"The objective of this study has been to present current information regarding damage to field crops from ozone in Indiana. The value of damage to soybean, corn, and wheat for 1978 was estimated to be $122.8 million with $121.4 million due to soybean damage; the balance is wheat damage, and no damage is estimated for corn. As the predominant damage is for soybean, the study concentrated discussion in that area."

"We have also shown how to obtain an estimate of the annual loss which might be expected to occur in any year in the 1980's given current best information about ozone, crop yield effects, and economic variables. Although there is some uncertainty involved in making such assessments of damage, we have shown how uncertainties may be dealt with explicitly by estimating expected values. The expected value of State income loss due to soybean damage was estimated to be $103.8 million in 1977 dollars."

Mjelde, James W., Richard M. Adams, Bruce L. Dixon, and Philip Garcia. "Using Farmers' Actions to Measure Crop Loss Due to Air Pollution," Journal of the Air Pollution Control Association, Vol. 31, No. 4, April 1984. 360-364.

"This study undertakes an innovative approach to measuring the effect of characteristics of the ambient environment on agricultural production in a major feed grain producing state. (Illinois) The methodology uses the economic theory of duality between production functions and profit functions to identify the effects of ambient ozone concentrations on the output, profitability and demand for variable inputs. An important aspect of this assessment approach compared with those which depend directly on dose-response functions is that the effect of ozone is measured for actual field conditions which reflect the reaction of economic agents (farm operators) to ambient ozone levels. When combined with existing biological evidence of yield effects, the only direct cost is for data collection. Also, the necessity of continuing plot experiments over time is obviated because such behavioral data typically exist over multiple years."



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"Because of the close linear relationship of ozone and temperature, additional information is used to help measure for the effect of temperature. The use of this physical science information shows how behavioral data and physical science data can be fruitfully combined to estimate both the economic reactions of producers and the physical change in supply to an ambient environmental characteristic."

"The estimated model shows ozone has the expected negative effect on profits..." (From corn and soybeans.)...."Additionally, increases in ozone levels are observed to depress output levels and to lessen the demand for variable inputs. At the average levels observed for the sample data a 1% increase in ozone would lead to a 0.408% decrease in profits.* Supply response is also equal to the same value. The estimated effect of marginal changes in ozone is not constant and as ozone levels rise the effect on profits becomes greater than the estimated 0.408%. This effect is partially the result of the model selected for estimation but is consistent with economic theory and estimated dose-response functions. This suggests the duality approach is a potentially viable method for estimating the impact of environmental effects."

..."Without some evidence of ozone-induced physical damage to plants, one would have no prior reason or justification for including ozone in an econometric model as a means of searching for the impact of ozone....Hence, assessment of economic loss due to pollutants is dependent on both economic and biological research..."

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* [Should be regarded as an upper limit.] "...computed under the assumption that price remains constant....With a decrease in supply from a dominant grain producer such as Illinois, prices received would increase, which would decrease the loss." (of profit)

Moskowitz, Paul D., Elizabeth A. Coveney, William Medeiros, and Samuel C. Morris. "Oxidant Air Pollution: A Model for Estimating Effects on U.S. Vegetation," Journal of the Air Pollution Control Association, Vol. 32, No. 2, February 1982. 155-160.

"This paper compares results of two different approaches for estimating some national-level economic effects of oxidants on a selected crop--alfalfa. The first uses a modified version of the Stanford Research Institute (SRI) plant impact model, developed by Benedict, et. al." [See entry in this bibliography.]

"Two inherent weaknesses remain in the SRI approach: (1) Use of emission estimates rather than actual air-quality measurements to represent dose; and, (2) use of subjective sensitivity functions based on foliar injury rather than mechanistic dose-response functions to express pollutant impact on crop yield."



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"The second approach, responding to the weakness in the SRI model, constructs a new model (DAMAGE) which uses...." "Actual air quality oxidant measurements as input to the Oshima dose-response function for alfalfa. Analyses from DAMAGE show that the economic loss estimates are highly sensitive to the method of aggregating air quality measurements to represent dose...."

"Economic loss is then simply calculated by multiplying crop value by percent loss. Estimates of oxidant effects on alfalfa in 1974 were calculated with both DAMAGE and the SRI model. Results of the SRI model closely approach those of DAMAGE when the dose estimate is approximated by the seasonal total of the hourly averages. Other methods of estimating dose in DAMAGE give d'stinctly higher estimates of economic loss. The lower bound estimates suggest losses equal to $20 million or 4% of the total yield in the counties examined. Upper estimates suggest losses as high as $200 million or a 36% reduction in yield."

Page, Walter P. "Economic Analysis of Agricultural Losses from Acid Precipitation," Acid Precipitation: The North American Challenge. Proceedings of a conference held October 25-28, 1982 in Burlington, Vermont. Soil Conservation Society of America, Ankeny, Iowa, 1983. 4-1 to 4-51.

"Our overall conclusions are as follows:

- Using base period parameter estimates, potential losses to producers of hay and corn in the five-state region, 1979, are on the order of $64,738,236;
- For the five-state region, 1979, the losses in producer surplus constitute on the order of 8.2% of potential clean-air producer surplus values.
- The five-state region losses are highly concentrated in two states, New York (78.1%) and Vermont (10.9%).
- For each of the states taken individually, losses to corn and hay producers tend to be on the order of 8.2% of producer surplus for clean air.
- In each state, as well as for the five-state region, losses to corn production in the presence of dirty air is 6% of potential clean-air producer surplus while for the case of hay the percentage figure is 10%.
- The calculation of losses in the region is most sensitive to variations in the price of crops or the estimated physical damage coefficients. Losses appear not to be particularly sensitive to the estimated supply elasticities for the crops."



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Page, Walter P., Gary Arbogast, Robert G. Fabian, and James Ciecka. "Estimation of Economic Losses to the Agricultural Sector from Airborne Residuals in the Ohio River Basin Region," Journal of the Air Pollution Control Association, Vol. 32, No. 2, February 1982. 151-154.

"The purpose of the research is to estimate monetary losses to agricultural producers in the study region from airborne residuals."

Monetary losses are defined as "producer surpluses" from corn, soybean, and wheat output which are less than they would be if the air were clean. Alternative losses for three different 1976-2000 scenarios are reported. The scenarios represent three alternative sets of energy use and pollution control assumptions, each falling short of the completely clean air ideal, against which the scenarios are judged.

"In this analysis, it is assumed that regional producers are price takers. That is to say, producers of [corn, soybeans, and wheat] operate in competitive markets and variations of individual output levels do not influence market prices. Producer losses are discounted at a 10% discount rate. Discounted losses have been summed over the years 1976-2000 in order to estimate the present discounted value of cumulative producer surplus losses..."

"In the case of Scenario 2 [1976 policies and business as usual], total regional losses constitute aproximately 10.3% of the discounted value of pollution-free output [of corn, soybeans, and wheat] over the 1976-2000 period. These losses uniquely attributable to [electric] utilities constitute approximately 4.3% of pollution-free output. Losses are unevenly distributed with respect to the ORBES-related portion of each state. [ORBES=Ohio River Basin Energy Study.] Illinois, which constitutes 53.6% of total regional losses, has the single largest loss within the region. This is followed by Indiana, with 25.1% and then by Ohio with 13.9%. The remaining states constitute only a small fraction of the total regional losses from airborne residuals: Kentucky is 6.1%, Pennsylvania is 0.4%, and West Virginia is 0.1%..."

"...[T]he overwhelming percentage of total dollar losses within the region are attributable to ozone concentrations....[O]zone concentrations within the region are related to nitrogen oxide emissions from power plants. This finding is of some significance in that only in the case of Illinois are there SIP [State Implementation Plan] requirements concerning nitrogen oxide emissions. As a consequence, compliance or noncompliance [with the SIP's] does not matter a great deal with respect to monetarized agricultural damages, although it does matter a great deal with respect to the level of sulfur dioxide emissions. As sulfur dioxide emissions account for only on the order of 1% of total monetarized agricultural losses within the region, the [SIP] standards are of little significance. The conclusion, then, is that if agricultural damages are of importance to those living within the region, efforts should be made to investigate the possibility of nitrogen oxide emission standards..."



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Smith, Martha, and Deborah Brown. Crop Production Benefits from Ozone Reduction: An Economic Analysis, Station Bulletin No. 388, September 1982, Dept. of Agricultural Economics, Agricultural Experiment Station, Purdue University, West Lafayette, Indiana.

"This study used the Purdue Crop Budget Linear Programming Model (B-9) to model a 720 acre farm in each of the nine Indiana crop reporting districts....The purpose of dividing the state into nine regions was to capture some of the basic differences caused by temperature, precipitation, soil type, water availability and distance to markets (which might affect the price the farmer receives). A 720 acre farm was assumed to be typical of a full-time farm business....[The authors] hypothesized an improvement in air quality levels. In this case, all crop yield changes will be in the form of improved yields possible if ozone levels fell. A base case and four yield improvements were run....The Purdue Crop Budget linear programming model (B-9) was created to help farmers find an optimal farm plan, one which maximizes profits from crop operations in one year."

"The parameters for each farm are in the form of activities and constraints. Each activity carries a revenue, or cost per unit of activity. Profit is determined by subtracting the sum of all costs from the sum of all revenues. Profit is maximized through the choice of activities and activity levels."

"Five crops are modeled: Corn, soybeans, wheat, double-crop soybeans and corn silage. Double-crop soybeans are grown after the winter wheat is harvested; therefore, double-crop soybean acreage is constrained to not exceed the wheat acreage....Input data are collected from the farmer for such parameters as total acreage, acres in each crop, available resources, operations necessary for each crop, and costs and prices expected. Model B-9 has values for a "Base Case" built into the model....The B-9 output consists of two plans; a present plan maximizes profit given the acreage in each crop as reported by the farmer. The optimal plan allows those acreages to change...."

"In order to compare cropping patterns and farmer net revenue between yields, the optimal (profit maximizing) plan for each region's actual yields was compared with the optimal plan for improved yields. In order to compare net farm revenues with crop substitution to those without substitution, plans which allowed acreage to shift as yields changed were compared to plans which constrained acreage to equal that which was optimal under current yields. Because an increase in yields may result in price effects, one needs to ascertain the results of yield improvements under different price scenarios. Soybeans are affected most by ozone; therefore, one would expect a decrease in ozone to result in some shifting of land to soybean production from other crops. To do a very rough estimate of price effects resulting from such a shift, models were run for the different regions under Alternatives 3 and 4 (the alternatives with significant changes in crop patterns) decreasing the soybean/corn price ratio by an arbitrary 5%."



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"By comparing the acreage in each crop under different yield improvement scenarios it can be seen that as ozone levels fall there is a shift from corn and wheat--crops more resistant to ozone damage--to soybeans, which are hurt more by the presence of ozone. When there is a substantial shift from corn and wheat to soybeans, as occurs under Alternatives 3 and 4, the price of soybeans may be affected due to the increase in supply of soybeans. As the price of soybeans drops relative to corn, one would expect a smaller shift to soybeans. To estimate the effect on net income and acreage, data was run for Alternatives 3 and 4 assuming a 5% decrease in the soybean/corn price ratio. This price decrease still leads to a shift in acres between the three crops. Under Alternative 3 there is a shift from soybeans to corn in all regions, and wheat acreage also increases in five regions. Under Alternative 4, a shift from soybeans to corn occurs in all regions, and an increase in wheat acreage occurs in the Northwest region. [The farm in each region defined as 'typical' of the region]. Income gains [because of ozone reduction and soybean yield increases] now range from $3220 to $5270 (per farm per year) under Alternative 3, and from $4857 to $9791 under Alternative 4." [Under Alternative 3 soybean yields rise by 5 percent, under Alternative 4 by 26 percent.]....

"This study uses early ozone damage estimates; these estimates may change as more research in that area is done....One must also remember that this is a one year model which ignores rotation patterns over several years. A shift to soybeans would presumably be inhibited by an existing pattern of corn-soybean rotation. On the other hand, presumably, a shift to soybeans would be encouraged where there is currently a pattern of continuous corn....Also, of course, by dealing only with one 720 acre farm in each region the total effects in each region are not estimated. To estimate the total benefits that could be achieved in Indiana through the reduction in ozone levels the supply and demand curves for the crops must be estimated."

U.S. Environmental Protection Agency. Benefits Analysis of Alternative Secondary National Ambient Air Quality Standards for Sulfur Dioxide and Total Suspended Particulates, Benefits Analysis Program, Economic Analysis Branch, Research Triangle Park, North Carolina, August 1982.

[The report examines] "[t]he economic benefits of achieving alternative secondary national ambient air quality standards (SNAAQS) for sulfur dioxide ($SO_2$) for....cotton and soybeans....Based on a sample of cotton-producing counties in Alabama, Arizona, California, Mississippi, New Mexico and Texas, a significant negative relationship between $SO_2$ and cotton yield has not been found....A significant negative relationship between ambient $SO_2$ levels and soybean yield has been found to exist for the sample counties in the states of Illinois, Indiana, Iowa and Ohio....The discounted present value in 1980 of the economic benefits of the reduction in $SO_2$ levels in these counties to this alternative secondary standard by 1988 are estimated to be $21.6 million in 1980 dollars."



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## Effects on Soils

### Surveys and Reviews

Alexander, Martin. "Effects of Acid Precipitation on Biochemical Activities in Soil," Ecological Impacts of Acid Precipitation, Proceedings of an International Conference, Sandefjord, Norway, March 11-14, 1980. Ed. D. Drablos and A. Tollan. SNSF Project, Oslo, Norway, October 1980. 47-52.

Soil acidification because of acid precipitation will likely cause serious adverse consequences in at least certain soils, especially forest soils. However, available data are not nearly broad enough for definitive conclusions. Not enough kinds of soils have yet been studied, nor have enough of the biochemical processes within soils been studied under the stress of acidification from rainfall. As a result, it is not yet possible to integrate all observations into a model soil-ecosystem approach. Nevertheless, from information now available, acid rain, particularly of an acidity of pH 3.2 and greater, probably adversely affects rates of nitrogen mineralization in some soils, nitrification, and organic matter decomposition. Acidification can have favorable impacts, however, on some soils. Reasons need to be explored.

Alexander, Martin. "Effects of Acidity on Microorganisms and Microbial Processes in Soil," Effects of Acid Precipitation on Terrestrial Ecosystems. Ed. T. C. Hutchinson and M. Havas. Proceedings of the NATO Conference on Effects of Acid Precipitation on Vegetation and Soils, held in Toronto, Canada, May 21-27, 1978. Plenum Press, New York, 1980. 363-374.

Many soil microbial processes important to plant growth are clearly suppressed as pH declines. However, a generalization about all or most microbial processes cannot be made, because harm to soil microorganisms noted in one soil at a given pH is not observed in another soil at the same pH. Where there is harm, it can be attributed to greater acidity of precipitation as observed, but where there is no injury to microbial processes with the same acidity the reasons are not known. Although the information base on the effects of soil acidification on microorganisms is reasonably large, areas of ignorance are even larger. A big deficiency is that relatively few soils, of the vast number of soils that exist, have yet been examined for acidification effects. And since the effects on microorganisms seem to be very much soil-specific or location-specific, generalizations have to be ruled out at this time. Moreover, short term trials based on stress effects (such as acidification) on soil microorganisms may be misleading, because some of these organisms are able to adapt to changed pH, although others cannot. Furthermore, consequences of greater acidity in the subterranean microbial ecosystem are not clear at all.



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Arthur, M. F. and C. K. Wagner, Ed. Response of Agricultural Soils to Acid Deposition: Proceedings of Workshop Conducted May 12-13, 1981 at Battelle Columbus Laboratories. Sponsored by Electric Power Research Institute (EPRI), EPRI Report EA-2508, EPRI, Palo Alto, California, July 1982.

Authors W. W. McFee, R. A. Olson, C. V. Cole with J. W. B. Stewart, and J. J. Mortvedt, presented working papers which are cited individually in this bibliography under each author's name.

In addition, the editors (from Battelle) include in the Proceedings an extensive review of relevant scientific literature, which they summarize as follows: "Agricultural soils which receive fertilizers and limestone likely will be minimally impacted by atmospheric acid deposition. Data presented in this brief literature survey indicate that even in potentially sensitive agricultural soils, impacts due to acid deposition can be ameliorated with proper management. However, long-term effects on sensitive soils may require more intensive study, especially with respect to weathering processes, soil buffering capacity, metals mobilization, and soil biota. The data of Ulrich et al. (1980) suggest potentially severe consequences of acid deposition on certain susceptible forest-type soils. Prevention of similar effects on agricultural soil is of utmost importance in sustaining crop productivity."

"On the other hand, atmospherically deposited sulfur and nitrogen appear to be beneficial to agricultural soils. Sulfur deposition has been cited as the mechanism preventing sulfur deficiencies in modern crop production."

"Obtaining accurate measures of dry deposition onto soils and plants appears to be a critical area limited by available methodology. To accurately assess effects due to acid deposition, quantitative analyses of total acidogenic inputs must be made. This may be most critical in those areas containing soils suspected of being sensitive to acid deposition. Since wetfall is relatively easily measured, most reports have addressed this aspect of the acid-deposition problem. The literature indicates that dryfall may be as substantial as wetfall and should be examined more closely."

Bache, Byron W. "The Sensitivity of Soils to Acidification," Effects of Acid Precipitation on Terrestrial Ecosystems. Ed. T. C. Hutchinson and M. Havas. Proceedings of the NATO Conference on Effects of Acid Precipitation on Vegetation and Soils, held in Toronto, Canada, May 21-27, 1978. Plenum Press, New York, 1980. 569-572.

Considerable loss of calcium from calcareous soils occurs because of acid deposition. Changes toward soil acidity may occur on noncalcareous soils of higher pH levels, but under these conditions it is not a serious matter. Where further soil acidification would be likely to have serious consequences, such as in highly unsaturated acidic soils, it is most unlikely



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to occur because of acid rain. However, there is an intermediate range of slightly-acid, poorly-buffered, shallow, sandy soils where relatively little acidification may lead to a striking loss of productivity. Such soils, if devoted to agriculture, would present no problems, because they can be readily limed. They are more difficult to deal with where land is in forest, because of the costs involved in liming large tracts of inaccessible land. Such sites should be carefully monitored for effects of acid rain, and they present the most suitable material for experimental study.

Black, C. A. "Additional Facts You Should Know About Acid Rain," Crops and Soils Magazine, American Society of Agronomy, Vol. 33, No. 8, June/July 1981. 5-8.

The author believes that some of the previously published adverse effects attributed to acid rain do not represent a balanced view. He highlights the following: "(1) [T]he sulfur and nitrogen in acid rain are plant nutrients; (2) soils and lakes become acid from natural causes as well as from acid rain; (3) the amount of acidity produced in agricultural soils by acid rain is small in relation to acidity produced there by other causes." Crop requirements for nutrient sulfur range between 8 and 85 pounds per acre per year, roughly comparable to the amount of sulfur falling to earth annually in acid rain of pH 4.0 in the Northeast. Crop requirements for added nitrogen of between 50-150 pounds per acre per year are hardly fulfilled at all, however, by nitrogen in acid rain in the Northeast, averaging only about 2.4 pounds per acre per year.

Cronan, Christopher S. "Consequences of Sulfuric Acid Inputs to a Forest Soil," Atmospheric Sulfur Deposition: Environmental Impact and Health Effects. Ed. D. Shriner, C. Richmond, and S. Lindberg. Proceedings of the Second Life Sciences Symposium, Gatlinburg, Tennessee, October 14-18, 1979. Ann Arbor Science, Ann Arbor, Michigan, 1980. 335-344.

"One of the important concerns regarding acid precipitation and global sulfur pollution is the question of how acid rain and snowmelt interact with the soil system. Studies concerned with the ecological effects of atmospheric $H_2SO_4$ and $HNO_3$ upon soils have shown the following results: (i) Atmospheric inputs of sulfuric acid may shift leaching processes from organic and carbonic acid control to sulfuric acid dominance throughout the soil zone of some forest ecosystems; (ii) in regions of noncalcareous bedrock, acid rain and acid snowmelt may alter aluminum transport, resulting in increased aluminum leaching through soils and into streams; (iii) depending upon environmental conditions, acid precipitation may cause increased leaching of essential nutrient cations from soils; and (iv) the impact of acid precipitation upon forest soils may be influenced in part by vegetation status and acid buffering processes in the forest canopy, by soil physical-chemical properties, and by geographic factors."



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Frink, C. R. and G. K. Voigt. "Potential Effects of Acid Precipitation on Soils in the Humid Temperate Zone," Water, Air, and Soil Pollution. Vol. 7, No. 3, March 1977. 371-388.

"Unmanaged soils in the northeast United States generally tend toward increasing acidity which results from several natural processes in the soil. Possible effects of acid precipitation on these processes may be caused by hydrogen ions associated with excess anions in the precipitation and, in addition, the anions may also have specific effects. This is especially true for N and S both of which have important biological implications. It is likely that the direct effects of the H ion will be modest....Additions of acid in rainfall to agricultural soils are insignificant in comparison with acidity produced by agricultural soil amendments. Moreover, this acidity is readily neutralized by additions of limestone in the normal course of agricultural practice."

"In unmanaged soils, acid rainfall might be expected to have more pronounced effects. However, acidity produced by biological cycling of N and S compounds in forested stands exceeds that found in rainfall at present. Moreover, the pronounced buffering exerted by soil minerals and organic matter tends to minimize changes in soil pH when acids are added. If acidity in precipitation should increase substantially or if the buffering capacity of the soil ecosystem is seriously reduced, we would expect detrimental changes in soil productivity. At present, however, acid precipitation does not appear to pose a serious threat to soils in the Northeast."

Hornbeck, James W. "Acid Rain: Facts and Fallacies," Journal of Forestry, Vol. 79, July 1981. 438-443.

"Acid rain carries not only substances that donate hydrogen ions, such as nitric, sulfuric, and organic acids, but also other dissolved ions, including common and heavy metals and trace elements. In this respect, acid rain has beneficial as well as adverse aspects. Beneficially, it contains nutrients such as calcium, potassium, sulfur, nitrogen, and trace elements, often in a form readily available for plant use. Also the initial result of soil leaching may be to enrich aquatic systems in metal ions such as calcium. Adversely, acid rain may have the potential to slow productivity, alter species composition, and impoverish terrestrial ecosystems by increasing the leaching of nutrient ions and interfering with biologic processes such as decomposition of organic matter."

"The consensus of biologists and geochemists is that the potential adverse effects far outweigh the potential benefits.....For foresters, concern usually centers around three subjects: aquatic ecosystems, soils, and forest vegetation....."

"Gradual acidification of soils is a natural phenomenon in regions where precipitation is sufficient to leach basic cations such as calcium from



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the surface layers. The concern is that the addition of strong mineral acids will accelerate the replacement and leaching of basic cations and speed the rate of acidification.....This concern is not so great for agricultural soils, where increases and decreases of soil acidity by fertilization and liming normally overshadow chemical inputs in precipitation. It may be justified for forest soils, however, particularly those that are shallow, coarse textured, and already lacking in basic cations...."

"Either indirectly through changes in the soil or directly by effects on foliage, acid rain may ultimately reduce forest productivity and alter species composition or diversity. Potential impacts as suggested by a variety of field and laboratory research have been listed....but have not yet been shown to occur in natural environments....One major concern is that damage to the cuticular layer that protects foliar organs could lead to possible injury of surface cells, water stress, and leaching of minerals from foliar surfaces....It appears that effects on forest vegetation are going to be extremely difficult to quantify. A major problem is that methodology for measuring forest productivity over large areas is not sensitive enough. As a further complication, the initial weakening and mortality of foliage may be masked by an increase in disease or insect damage...."

Klopatek, Jeffery M., W. Frank Harris, and Richard J. Olson. "A Regional Ecological Assessment Approach to Atmospheric Deposition: Effects on Soil Systems," Atmospheric Sulfur Deposition: Environmental Impact and Health Effects. Ed. D. Shriner, C. Richmond, and S. Lindberg. Proceedings of the Second Life Sciences Symposium, Gatlinburg, Tennessee, October 14-18, 1979. Ann Arbor Science, Ann Arbor, Michigan, 1980. 539-553.

"A regional ecological overview of the potential effects of acid precipitation on soils is presented. Computer maps of soil pH, cation exchange capacity (CEC), base saturation, and base content in the Eastern United States are displayed using county level data. These maps are overlain with a computer map of the hydrogen ion loading, and resultant maps of acid-sensitive and acid-insensitive soils are presented. Of the 1572 counties in the eastern United States, only 117 are classified as being acid-sensitive."

However, there are several qualifications, as follows: The hydrogen ion data do not include contents of basic elements in rainfall; rain acidity does not include dry deposition; acidity accumulation in snowpack can influence timing and amount of acidity release to streams and lakes; the nature of the soil parent weathering material can moderate rain acidity; reactions to acid rain in the vegetation canopy, along stems, and in litter tend to buffer the acidity; and land management practices, such as liming of crop land, add basic elements.



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Thus, "[t]he addition of hydrogen ions in precipitation is a small contribution under all but the most extreme conditions."

In general,the study "points out locations where there is a high probability of impact and areas where site-specific studies should take place."

Krug, Edward C. and Charles R. Frink. "Acid Rain on Acid Soil: A New Perspective," Science, August 5, 1983. 520-525.

"Acid rain is widely believed to be responsible for acidfying soil and water in areas of North America and Northern Europe. However, factors commonly considered to make landscapes susceptible to acidification by acid rain are the same factors long known to strongly acidify soils through the natural process of soil formation. Recovery from extreme and widespread careless land use has also occurred in regions undergoing acidification. There is evidence that acidification by acid rain is superimposed on long-term acidification induced by changes in land use and consequent vegetation succession. Thus, the interactions of acid rain, acid soil, and vegetation need to be carefully examined on a watershed basis in assessing benefits expected from proposed reduction in emissions of oxides of sulfur and nitrogen."

McFee, William W. "Effects of Atmospheric Pollutants on Soils," Polluted Rain. Ed. T. Y. Toribara, M. W. Miller, and P. E. Morrow. Proceedings of the Twelfth Rochester International Conference on Environmental Toxicity, University of Rochester, Rochester, New York, held May 21-23, 1979. Plenum Press, New York, 1980. 307-323.

"Atmospheric pollution of soils appears to be a problem where susceptible soils coincide with zones of very acid precipitation and anywhere toxic metals are accumulating. However, soils appear to be much more tolerant to acid precipitation than many aquatic and plant systems due to the chemical buffering capacity provided by clay and organic matter. In unmanaged soils of forests and wildlands, soil acidification may be significantly accelerated by the acid precipitation currently experienced if the dominant soils are low in exchange capacity."

"It will probably require time spans on the order of decades to measure the effects on soils even where they are poorly buffered. The effects on site productivity are difficult to predict due to the multiple effects of additional acid. Increased weathering and the nitrate and sulfate ions in the precipitation may provide nutrients that were formerly limiting, and thus, increased productivity may be noted. Long term effects on the soil are generally considered to be negative since the loss of basic cations, reduction in cation exchange capacity, and accelerated weathering ultimately lead to soils of lower natural productivity. Long term field studies



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are needed to determine if remedial action is needed on soils that are presently unmanaged. Acid precipitation effect on agricultural systems may be important in its direct effect on plants, but the soil effect will be completely masked by normal soil amendments already in use. Metal contamination of soils needs to be monitored closely. The potential effects are serious and long lasting. Reports available indicate low levels of metal accumulation are widespread in industrial nations, but toxic levels are presently found only near major point sources. Some of these point sources have influenced significant areas. Other sources of metals added to the soil should be considered also when evaluating tolerable atmospheric deposition. There is likely to be an interaction between acid precipitation and soil metal levels since acidity increases metal mobility in the soil."

McFee, William W. "Sensitivity of Soil Regions to Long-Term Acid Precipitation," Atmospheric Sulfur Deposition: Environmental Impact and Health Effects. Ed. D. Shriner, C. Richmond, and S. Lindberg. Proceedings of the Second Life Sciences Symposium, Gatlinburg, Tennessee, October 14-18, 1979. Ann Arbor Science, Ann Arbor, Michigan, 1980. 495-505.

"Criteria for ranking soil sensitivity to the effects of acid precipitation are discussed. A ranking scheme based on cation exchange capacity and presence or absence of carbonate in the top 25 cm. of soil and presence or absence of flooding was devised. Five map units varying in potential sensitivity and percentage of the area considered sensitive were used to map the eastern United States. Maps of New York, North Carolina, West Virginia, Pennsylvania, and Indiana are presented. It is recognized that other factors could be considered to improve the ranking scheme and that land use, which is ignored in these maps, has an effect overshadowing that of acid precipitation. The maps should be useful in research planning and in selecting areas for intensive study. The ranking of sensitivities is not intended to predict severity of effects but to guide the selection of terrestrial and aquatic sites to areas where the potential for adverse impacts of long-term atmospheric deposition are the greatest. The need for field testing of the system is obvious."

McFee, William W. "Sensitivity Ratings of Soils to Acid Deposition: A Review," Response of Agricultural Soils to Acid Deposition: Proceedings of Workshop Conducted May 12-13, 1981 at Battelle Columbus Laboratories. Ed. M. F. Arthur and C. K. Wagner. Sponsored by Electric Power Research Institute (EPRI), EPRI Report EA-2508, EPRI, Palo Alto, California, July 1982. 2-1 to 2-12.

"It is clear that soils vary in many properties within the geographic region influenced by acid precipitation. The rapidity and even direction of changes induced by acid precipitation are bound to be influenced by



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these properties....At least three publications have attempted to categorize soil regions according to their sensitivity. This exercise is quite different from a discussion of the properties that influence sensitivity because limitations are imposed by availability and reliability of data on the soils of interest. Variability within a soil and inclusion of other soils within mapping units severely limit the interpretations that can be made. Also, there are obviously many unknown or poorly defined rates of change in the field that complicate predictions of susceptibility to acid precipitation. For example, the base replenishment from dust deposition, nutrient cycling, or mineral weathering [is] seldom known."

"McFee (1980) developed a relatively simple scheme for grouping soil regions into sensitivity classes. After grouping all soils that are calcareous or subject to frequent renewal by such events as flooding into the nonsensitive group, he classified the others on the basis of cation exchange capacity. Many of the potentially serious soil effects are tied to changes in pH which are controlled by cation exchange capacity..."

"All of the attempts at classifying soil sensitivities were aimed at broad, regional mapping, and for that reason, had to use data generally available and had to ignore many inclusions of mapping units and variation within soils. All are based on hypothetical inputs of acid in excess of those commonly experienced today and on idealized concepts of exchange reactions and base saturation-pH relationships. All that any of them can hope to do is indicate which soils should be examined first in a search for acid deposition effects. They certainly do not define regions where most soils (perhaps, not any) are being significantly damaged by the present regime of acid deposition."

McFee, W. W., F. Adams, C. S. Cronan, M. K. Firestone, C. D. Foy, R. D. Harter, and D. W. Johnson. "Effects on Soil Systems," The Acidic Deposition Phenomenon and Its Effects: Critical Assessment Review Papers, Volume II, Effects Sciences. Eds. Aubrey P. Altshuller and Rick A. Linthurst. EPA Report 600/8-83-016BF, Office of Research and Development, U. S. Environmental Protection Agency, Washington, D. C., July 1984. 2-1 to 2-69.

[From the Preface to Vols. I and II: "The document's original charge was to prepare 'a comprehensive document which lays out the state of our knowledge with regard to precursor emissions, pollutant transformation to acidic compounds, pollutant transport, pollutant deposition and the effects (both measured and potential) of acidic deposition.'" Volume I concerns the atmospheric aciences, while Volume II (as noted above) covers the effects sciences. More than 50 scientists contributed to the report.]

Conclusions

" - Soils amended in agricultural practice will not be harmed by acidic deposition.



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- Soils acidification is a natural process in humid regions. It is obvious that acidic deposition contributed to this process; however, at current levels, it is a minor contribution.
- Most soils of low buffering capacity in areas of high rainfall are already acid; therefore, few soils are likely to become perceptibly more acid due to deposition. They are the soils that have low buffering capacity, a relatively high pH (slightly acid, pH 5.5 to 6.5), low sulfate adsorption capacity, no carbonates, and no basic inputs.
- The availability of sulfur and nitrogen to plants will be enhanced by their presence in the deposition....Benefits of sulfuric acid deposition are probably minimal...."
- The long-term effect (i.e. over decades or centuries) of acidic deposition can be expected to remove cations from forest soils, but it is not clear whether this will reduce available cations and enhance acidification of soils. For example, cation leaching rates, although increased by acid precipitation, may remain insignificant relative to total soil supplies....
- ....It cannot be stated that forest ecosystems, in general, respond to acidic deposition in a single predictable way. Indeed, the contrasting behavior of Norway spruce in Germany and in Norway exemplifies the variable response that can be expected from different sites.
- ....If soil pH is low enough (less than pH 5.0 to 5.5) in mineral soils to cause the dissolution of aluminum- and manganese-containing minerals, hydrogen ion input will increase release of aluminum and manganese to the soil solution.
- The increased availability of aluminum in uncultivated, acid soils is probably the most significant effect of acidic deposition on soils as they influence terrestrial plant growth and aquatic systems.
- ....Unless average precipitation inputs were to drop to pH 3.0 or below, significant impacts of acidic deposition on litter decomposition in natural systems are not expected.
- Soil microbial activity....Evidence for effects of acidic deposition on Rhizobium or actinomycete symbiotic nitrogen fixation remains inconclusive....Important effects under field conditions have not been clearly demonstrated."

McFee, William W. and Christopher S. Cronan. "The Action of Wet and Dry Deposition Components of Acid Precipitation on Litter and Soil," Acid Precipitation: Effects on Ecological Systems. Ed. Frank M. D'Itri. Proceedings of the Conference on the Effects of Acid Precipitation on Ecological Systems, Michigan State University, East Lansing, 1982. Ann Arbor Science, Ann Arbor, Michigan, 1983. 435-451.

[Potential effects], "....taken together, present the possibility of serious damage to the soil's ability to support vigorous plant growth and to protect the quality of water. However, this has not yet been confirmed as a general conclusion; there is still much research that is needed to permit a holistic assessment of this problem. Some of the evidence for



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these effects is based on experimental rates of acidic deposition far exceeding current loadings. The same amount of input spread over a much longer term may have a different net effect. Although many of the potential effects could result in decreased site productivity over the long term, no one has yet been able to demonstrate this conclusively. Offsetting effects may even occur in some instances. For example, an increased weathering rate of primary minerals may leave the supply of cations available for production unchanged even in the presence of increased leaching. Likewise, compensating shifts in microbial communities may result in a new dynamic equilibrium just as desirable as the previous one...."

"One of the difficulties with much of the writing concerning acidic deposition effects on soils has been our failure to differentiate clearly between effects of 'acidic deposition' and 'soil acidification.' The latter is an almost ubiquitous process in humid climates of the world. The effects of soil acidity on plant nutrition, soil chemical processes, and soil organisms have been studied for decades. Many of the undesirable effects of soil acidity have occasionally been attributed to acidic deposition without regard to the significance of soil acidification in bringing about the acid condition. Many natural phenomena influence this process of acidification as much or more than the phenomenon of acid precipitation...."

"A reduction in soil pH to 3.0 is not likely to occur as a result of acidic precipitation. It has been pointed out by several authors (Wiklander, 1973-74; Reuss, 1975; McFee et al., 1977) that reduction in soil base saturation and increases in soil acidity due to acidic precipitation would take quite a while, on the order of decades, for a noticeable shift to occur from that cause alone...."

"One of the potential ecological effects of acidic deposition is the increased mobilization of soil aluminum that may result. Changes in soil aluminum leaching may be indicative of changes in weathering rates, changes in base saturation, and changes in clay mineralogy and morphology; furthermore, increased aluminum concentrations in natural water may be harmful to plant and animal communities...."

"Under conditions where the mobility of the atmospheric sulfate (or nitrate) is not limited by adsorption or absorption processes, the anthropogenic strong acids may contribute to increased leaching of free inorganic aluminum from the B horizon to ground water and surface waters...."

"Both Norton's (Hendrey et al., 1980) and McFee's (1980) analyses of regional sensitivity indicated that a large portion of the Great Lakes region may be somewhat sensitive....In spite of their limitations, they do give us some indication that compared to much of the United States, there are numerous areas within the Great Lakes region that should be watched for evidences of acid precipitation effects...."



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McFee, W. W., J. M. Kelly and R. H. Beck. "Acid Precipitation Effects on Soil pH and Base Saturation of Exchange Sites," Water, Air, and Soil Pollution, Vol. 7, No. 3, 1977. 401-408.

"The typical values and probable ranges of acid precipitation are evaluated in terms of their theoretical effects on pH and cation exchange equilibrium of soils characteristic of the humid temperature region. The extent of probable change in soil pH and the time required to cause such a change are calculated for a range of common soils. Hydrogen ion input by acid precipitation is compared to cation inputs from nutrient cycling and other sources....The quantity of exchangeable basic cations that tend to buffer the soil against acidification is quite large in many soils.... [The] discussion points out the resistance of most soil systems to pH change, the small likelihood of rapid soil degradation due to acid precipitation, and the difficulty of evaluating this and associated changes in the normal experimental time frame."

Mortvedt, John J. "Impacts of Acid Deposition on Micronutrient Cycling in Agro-Ecosystems," Response of Agricultural Soils to Acid Deposition: Proceedings of Workshop Conducted May 12-13, 1981 at Battelle Columbus Laboratories. Ed. M. F. Arthur and C. K. Wagner. Sponsored by Electric Power Research Institute (EPRI), EPRI Report EA-2508, EPRI, Palo Alto, California, July 1982. 2-64 to 2-75.

"Micronutrient additions to soil result mainly from return of crop residues and application of fertilizers, farmyard manures, and municipal wastes. Crop removal and erosion of surface soil constitute the main micronutrient losses. Only a small fraction of total micronutrients in surface soils is cycled via cropping. Plant availability of all micronutrients except molybdenum increases with increasing soil acidity. Toxicities due to manganese and aluminum in extremely acid soil may result in decreased crop yields. Changes in soil pH due to acid depositions are minimal in most agricultural soils because of relatively high buffering capacities of these soils. Modern farming practices such as liming and return of crop residues also may override depositional effects. Therefore, micronutrient cycling in most agro-ecosystems should not be significantly affected by acid depositions. The long-term effects of acid depositions are not known..."

"Unless a soil is near the critical soil pH level for Mn and/or Al toxicity to occur (usually about pH 5.0), soil acidification due to acid precipitation should not have an adverse effect on plant growth. Decreases in soil pH would increase plant uptake of all micronutrients except molybdenum, but a large fraction of the increased uptake usually would be recycled to soil with the return of crop residues."

"The effects of acid precipitation may be greater on other ecosystems, however,"...such as forest ecosystems.



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Norton, Stephen. "Change in Chemical Processes in Soils Caused by Acid Precipitation," Proceedings of the First International Symposium on Acid Precipitation and the Forest Ecosystem, Columbus, Ohio, May 12-15, 1975. Ed. L. S. Dochinger and T. A. Seliga. Forest Service General Technical Report NE-23, Forest Service, USDA, 1976. 711-724.

"[The author] examines the changes in the nature of precipitation brought about by acid precipitation and the anticipated changes in mineral stability and element mobility in the rock-water chemical systems....The possible results of this precipitation falling on soil are: (1) Increased mobility of most elements....; (2) increased loss of existing clay minerals....; (3) a change in cation exchange capacity--in some situations an increase, in others a decrease; (4) a general proportionate increase in the rate of removal of all cations from the soil....; and (5) an increased flux of nutrients through ecosystems contiguous with the soil and through aquatic ecosystem below the soil zone."

Nyborg, Marvin and D. R. Walker. "An Overview--The Effects of Sulfur Dioxide Emission on the Acidity and Sulfur Content of Soils," Proceedings, Alberta Sulfur Gas Research Workshop III. Edmonton, November 17-18, 1977. 165.

"The international literature on the effect of $SO_2$ emissions on soils is reviewed. The great majority of researchers showed evidence that $SO_2$ causes soil acidification, in the vicinity of large sources....In Alberta there are approximately 2 million hectares of cultivated soils which are deficient in sulfur as shown by soil testing. However, because of the location of the sulfur-deficient soils and the apparent pattern of fallout from $SO_2$ emissions, the deficient soils receive little sulfur from emissions."

Olson, R. A. "The Impacts of Acid Deposition on Nitrogen and Sulfur Cycling," Response of Agricultural Soils to Acid Deposition: Proceedings of Workshop Conducted May 12-13, 1981 at Battelle Columbus Laboratories. Ed. M. F. Arthur and C. K. Wagner. Sponsored by Electric Power Research Institute (EPRI), EPRI Report EA-2508, EPRI, Palo Alto, California, July 1982. 2-13 to 2-34.

"There is reasonable cause for doubt, however, that the elevated levels of acid deposition will have any serious damaging effects on agricultural soils and crops other than in close proximity to large coal-burning plants..."

"The buffer capacity of soil or resistance to pH change varies with its cation exchange capacity such that it is only the poorly buffered types that would be likely to be acidified sufficiently over the time interval of a decade to require amendment for correction. On the other hand the fallout occurring on calcareous soils in the drier western half of the



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country would have no lime requirement and rather have added neutralizing value over a long period of time beyond the nutritional value, even increasing availability of some micronutrients to crops. Soils, because of this buffer capacity, are much more resistant to pH change than surface waters and are much less likely to be damaged by acid deposition than vegetation. It is projected that the only hazard situations in soil nitrogen and sulfur cycling are with nonaccessible soil areas in native forest having the combination of low clay and organic matter contents and shallowness of soil that is responsible for a low total cation exchange capacity, and especially where the soil was inherently somewhat acid. Here, without continuous monitoring, acid fallout might insidiously build up to the point where irreparable damage was done to the forest because of soil deterioration before corrective measures were attempted. Comprehensive monitoring will be essential, of course, in the close proximity of plants effecting major intrusions of sulfur and nitrogen compounds into the atmosphere."

Petersen, Leif. "Sensitivity of Different Soils to Acid Precipitation," Effects of Acid Precipitation on Terrestrial Ecosystems. Ed. T. C. Hutchinson and M. Havas. Proceedings of the NATO Conference on Effects of Acid Precipitation on Vegetation and Soils, held in Toronto, Canada, May 21-27, 1978. Plenum Press, New York, 1980. 573-577.

In general, the following soil orders (U.S. classification system) tend to include soils which are relatively sensitive to acid precipitation: Entisols, Inceptisols, Ultisols, Spodosols, and Oxisols. The remaining soil orders, Aridisols, Millisols, Alfisols, Vertisols and Histosols, are unlikely to be affected adversely by acid percipitation, or would be affected only to a small extent. However, because each of these orders (with its suborders and great groups) encompasses a very large number of individual soils, whose properties vary greatly, the above is merely a generalization. Any estimation of the sensitivity (or degree thereof) of a particular soil must be based on a detailed description of the properties of the soil and the composition of the precipitation.

Reuss, John O. "Chemical and Biological Relationships Relevant to the Effect of Acid Rainfall on the Soil-Plant System," Water, Air, and Soil Pollution, Vol. 7, April 1977. 461-478.

"[The author] deals with problems concerning measurements of rainfall acidity and interpretation in terms of possible effects on the soil plant system...[A]verage H+ concentration calculated from H measurements is not a satisfactory method of determining hydrogen ion loading from rainfall if the rain is not consistently acid..."



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"The flux of H+ ions in soil systems due to plant uptake processes and sulfur and nitrogen cycling is considered. H+ is produced by oxidation of reduced sulfur and nitrogen compounds mineralized during decomposition of organic matter. Plant uptake processes may result in production of either H+ or OH- ions. Fluxes of hydrogen ions from these processes are much greater than rainfall hydrogen ion inputs, complicating measurement and interpretation of rainfall effects. The soil acidifying potential due to the oxidation of the [ammonium contained in] rainfall is examined, with the conclusion that acidity from this source is of a similiar magnitude to direct hydrogen ion inputs common in rainfall..."

Rorison, I. H. "The Effects of Soil Acidity on Nutrient Availability and Plant Response," Effects of Acid Precipitation on Terrestrial Ecosystems. Ed. T. C. Hutchinson and M. Havas. Proceedings of the NATO Conference on Effects of Acid Precipitation on Vegetation and Soils, held in Toronto, Canada, May 21-27, 1978. Plenum Press, New York, 1980. 283-304.

Acid precipitation will probably make a substantial long-term impact by gradual acidification of those soils with relatively low buffering capacity. Some plants, however, have become well adapted to acidic conditions, where these conditions have occurred gradually and naturally. In general, acidic soils have relatively low levels of major nutrients, but relatively high levels of trace nutrients. The processes of plant adaptation to acidic soils and to those nutrient conditions are not yet fully understood, but research is advancing.

Voigt, G. K. "Acid Precipitation and Soil Buffering Capacity," Ecological Impacts of Acid Precipitation: Proceedings of an International Conference, Sandefjord, Norway, March 11-14, 1980. Ed. D. Drablos and A. Tollan. SNSF Project, Oslo, Norway, October 1980. 53-57.

The composition of the mineral substratum ultimately determines the ability of a soil to resist impacts of acid precipitation. Soils originating from geologic materials high in alkali metals and alkaline earth elements--that is, well buffered soils--are less likely to have adverse effects from acid precipitation. However, aluminum dissolved from soil minerals and released into solution by the action of percolating acids may have a toxic effect on plants and tiny soil animals, an effect which is separable from impact of acidity. Further aspects of the reactions of soil biota and minerals to acid precipitation are discussed in detail.



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Wiklander, Lambert. "The Acidification of Soil by Acid Precipitation," Grundforbattring, Vol. 26, No. 4, 1973/74. 155-164.

"The effect of acid precipitation on the soil has been studied on a theoretical basis by discussion of the cation exchange induced. The conclusions drawn are evidenced by some experimental data...."

"Acid precipitation and nitrified $NH_4^+$ have a strong cation replacing and dissolving effect in neutral and slightly acid soils, such as cultivated soils and many brown earths. In strongly acid soils, such as podsols and very acid brown earths, this effect is weaker."

"The adverse effects of acidic atmospheric compounds on soils depend on the buffering capacity against pH decrease and on the amounts of neutral salts deposited on the ground. Calcareous soils and cultivated soils, properly managed, show high buffering and low sensitivity, whereas uncultivated, slightly acid, sandy soils and loams are more sensitive to acidification."

Wiklander, Lambert. "The Sensitivity of Soils to Acid Precipitation," Effects of Acid Precipitation on Terrestrial Ecosystems. Ed. T. C. Hutchinson and M. Havas. Proceedings of the NATO Conference on Effects of Acid Precipitation on Vegetation and Soils, held in Toronto, Canada, May 21-27, 1978. Plenum Press, New York, 1980. 553-567.

Acid precipitation may or may not lead to adverse effects on soil and percolating water, depending largely on soil properties, but also on soil depth, climate, and topography, which help determine runoff rate. The phenomenon of acidification of soils and waters must consider all acidification sources, namely processes within the soil which yield acids, as well as acid inputs from the atmosphere. The active factor in acidification is the hydrogen ion. Its sources are: (1) Nutrient uptake by plants. As root substances absorb nutrients, they release hydrogen ions; (2) Carbon dioxide produced by plant roots and microorganisms; (3) Oxidation of ammonium, and sulfur/ferrous sulfide or disulfide, and hydrogen sulfide to nitric acid and sulfuric acid; (4) Very acid litter in coniferous forests; (5) Atmospheric deposition of sulfuric acid and some oxides of nitrogen, nitric/hydrochloric acids, and ammonium after nitrification. Based on ion exchange theory and experiments, and soil sample leaching, acid precipitation affects soils as follows:

At soil pH above 5.5, the acids are fully neutralized by decomposition of calcium carbonate and other unstable minerals and by cation exchange. At pH less than 5.5, the efficiency of the hydrogen ion in decomposing minerals and replacing exchangeable calcium, magnesium, potassium, and sodium decreases with the soil pH. Consequently, in the very acid soils, the acidifying effect of mineral acids on the soils decreases but the effect on the discharge water increases. The greater part of the acids percolates through the soil. Soil sensitivity to precipitation acidity



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depends on buffering capacity and on soil pH. Very acid soils are far less sensitive than less acid soils because they have already adjusted to acidity by soil formation. Easily weatherable minerals have disappeared. Clay soils buffer acid well and are only moderately sensitive. Calcareous soils are not sensitive until or unless their carbonate is dissolved. Noncalcareous, sandy soils with a pH greater than 5 are the most sensitive. In soils with a pH greater than 6, natural acidificaton processes dominate. In well managed cultivated soils, the mineral acid fallout means only a slight increase in lime required, with the cost offset by the supply of plant nutrients from the acid rain--sulfur, nitrogen, magnesium, potassium, sodium, and calcium.

Individual Studies

Baath, E., B. Lundgren, and B. Soderstrom. "Effects of Artificial Acid Rain on Microbial Activity and Biomass," Bulletin of Environmental Contamination and Toxicology, Vol. 23, No. 6, December 1979. 737-740.

The authors used artificially acidified rain to estimate effects on microbial activity and biomass in a Norwegian forest soil. Three forest areas were artifically watered with simulated rain of different acidities and also received natural rain, so that precipitation for the areas averaged pH 4.5, pH 3.4, and pH 2.5, respectively. Some key indicators of soil microbial activity were adversely affected in the pH 2.5 area, but not in the other areas. Other key indicators were not adversely affected in any of the test areas. The authors conclude: "Our results imply that the long-term effect of acidified rain could be decreased microbial activity. However, a direct comparison with the natural situation is difficult, since the artificial rain applied in this study had a much lower pH than natural rain."

Berigari, M. S. and P. B. Xerikos. "Leaching Rates of Several Cations from Soils by Simulated Rainwater," Annual Report: Argonne National Laboratory Radiological Environmental Research Division, Vol. ANL 75-60, 1976. 8-11.

"The effects of acid precipitation on the release of major cations from soil were studied by leaching or shaking soils with real and simulated acid rainwater. The amount of water used was equivalent to two years of rainfall in the Midwestern states....Treatment of the soils with solutions at pH's less than 4 significantly lowered soil pH....In general, the water with the lower pH removed the larger amounts of cations, and reversals in this trend occurred only above pH 5....Rainwater with a pH less than 4 could increase the rate of mineral weathering, especially in areas with moderate temperatures and high annual rainfall--typical of areas of great agricultural productivity....The impact of acid precipitation on soil and plant environ-



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ment appears to be very complex, and long-range studies will be required in order to understand these effects."

Bockheim, J. G., A. Prey, J. M. Esser, E. A. Jepsen, and J. Krawczyk. Interaction Between Acid Deposition and the Terrestrial Ecosystem in Northwestern Wisconsin. Annual report on project no. 2710 submitted to Wisconsin Department of Natural Resources. Department of Soil Science, Agricultural Experiment Station, University of Wisconsin, Madison, 1983.

Chemistry of bulk precipitation was monitored from the summer of 1981 to the autumn of 1982 in two small watersheds in northwestern Wisconsin. The pH of precipitation at both watersheds averaged 4.6. The dominant cation and anion in bulk precipitation were hydrogen and sulfate respectively. Although project data (as well as data from the literature) show increased loading of hydrogen, ammonium, sulfate, and nitrate ions and perhaps other chemical constituents, due to emissions from man-made sources, the project has not detected any effects of this increased loading on vegetational and soil properties and processes. Work continues through 1983.

Cole, C. V. and J. W. B. Stewart. "Impact of Acid Deposition on Phosphorus Cycling," Response of Agricultural Soils to Acid Deposition: Proceedings of Workshop Conducted May 12-13, 1981 at Battelle Columbus Laboratories. Ed. M. F. Arthur and C. K. Wagner. Sponsored by Electric Power Research Institute (EPRI), EPRI Report EA-2508, EPRI, Palo Alto, California, July 1982. 2-54 to 2-63.

"To date there have been few detailed studies specifically on the effect of acid deposition on soil organic phosphate forms or on the cycling of phosphorus under various cultivation systems. As depicted in the diagram of the phosphorus cycle, the microbial population is instrumental in the redistribution and/or accumulation of organic phosphorus compounds in soil. In considering these flows of phosphorus it will be important to relate the cultivation practice of a particular soil to both the amount of energy material that is incorporated during the cultivation practice and the amount of phosphorus in the soil solution..."

"The productivity of agricultural soils requires an active cycling of soil phosphorous pools through plants and microbial populations. Phosphorus cycling rates are thus closely linked to transformations of carbon, nitrogen, sulfur and other mineral nutrients. A systems approach to an understanding of factors controlling chemical and biological processes in ecosystems is necessary for an evaluation of the impacts of acid deposition on agricultural soils. Acid deposition effects on phosphorus cycling will be most pronounced on soils subject to intense weathering and erosional processes. Management practices developed to relieve these stresses will be most useful in mitigating impacts of acid deposition."



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Evans, Lance S., Keith F. Lewin, and Frank A. Vella. "Effect of Nutrient Medium pH on Symbiotic Nitrogen Fixation by Rhizobium leguminosarum and Pisum sativum (Pea)," Plant and Soil, Vol. 56, 1980. 71-80.

"The symbiotic relationship between legumes and members of the genus Rhizobium is important because gaseous nitrogen can be reduced to a form utilizable by plants. About 20 percent of all nitrogen fixation occurs via legume-Rhizobium symbioses. Since acidic soils are prevalent in the eastern United States and in many tropical countries, knowledge about the mechanism(s) limiting nitrogen fixation under acidic conditions may enable agriculturalists to increase world-wide protein production."

"Experiments were performed to measure the pH-sensitive steps in nodulation and symbiotic fixation by Pisum sativum and isolate RP-212-1 of Rhizobium leguminosarum. An aeroponic system with rigorous Ph control was used to obtain numerous effective nodules. After exposure to various pH levels, the following responses were measured: (1) Legume root growth and development, (2) survival and growth rate of a single effective bacterial isolate, (3) degree of nodulation, (4) rate of nitrogen fixation, (5) plant biomass, and (6) nitrogen content of plants. Both bacterial growth and root development were adequate at all pH levels from 4.4 to 6.6, but efficient nodulation and nitrogen fixation did not occur at pH 4.8 and below. The processes required for symbiosis were about 10 times as sensitive to acidity as either bacterial growth or root growth alone. Nodulation was the most acid-sensitive step."

Hsu, Hua, and G. W. Hodgson. "Organic Compounds of Sulfur: Initial Data for Soils and Streams in Alberta," Proceedings of the Alberta Sulfur Gas Workshop III, November 17-18, 1977. The Environmental Sciences Centre, (Kananaskis), The University of Calgary.

Agricultural soils in Alberta contain volatile organic compounds of sulfur. Under some circumstances, the number and abundance of these appear to be increased by about 30% by the outfall of sulfur emissions as revealed by sample pots placed close to sulfur recovery gas plants. Similar compounds are found in surface waters of rivers and lakes, commonly at a few micrograms per litre. These waters appear susceptible to outfalls from gas plants, with sharply increased contents of organic sulfur compounds, commonly more than ten times. In rivers, the effect is transitory, dying out within 10-15 km downstream.

Jones, U. S., M. G. Hamilton, and J. B. Pitner. "Atmospheric Sulfur as Related to Fertility of Ultisols and Entisols in South Carolina," Soil Science Society of America Journal, Vol. 43, 1979. 1169-1171.

"Contributions of atmospheric sulfur (S) to soil fertility at 15 locations in South Carolina were estimated during the 5-year period 1973-77 by



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measuring the S content of precipitation samples accumulated at 30-day intervals and by measuring the S collected in lead perioxide samplers exposed to the air at the same time intervals. The S content of precipitation was compared with similar data collected at three locations in 1953-55. Concurrently with the 1973-77, study long-term uniform field experiments designed to measure response of seven crops to S added in the fertilizer were conducted at selected locations.

"The mean estimated annual amount of S added to the soil in precipitation for the period 1973-75 was 11.3 kg per ha. The corresponding addition in 1953-55 was 6.3 kg/ha. The mean estimated amount of S added to the soil from the air and precipitation increased from 11.2 kg/ha in 1973 to 19.8 kg/ha in 1977. Sulfur added in the fertilizer resulted in an increased yield (10 percnet probability level) for (field corn and silage corn) at one location...." [However], "there has been no response during 1974-78 to fertilizer S, even at the 10 percent probability level, by sweet corn, barley, cucumber, snapbean, or turnip at the other location....It is evident from this research in the period 1973 to 1977 that S in the air is increasing. It is also evident, by comparing S in precipitation in 1953-55 to the fallout in 1973-75, that S in precipitation is increasing. For these reasons the findings and general recommendations for S fertilizer should be re-evaluated from time to time with carefully designed long-term field experiments such as those reported here."

"Twenty years ago S in the atmosphere made a minor contribution to the S required by crops in South Carolina (Jordan 1964). But current data indicate that atmospheric S is making a major contribution to the agronomic and horticultural crop needs for S as a plant nutrient."

Killham, K., M. K. Firestone and J. G. McColl. "Acid Rain and Soil Microbial Activity: Effects and Their Mechanisms," Journal of Environmental Quality, Vol. 12, No. 1, 1983. 133-137.

"In this investigation, our aim was to determine if acid rain affects soil microbial activity and to identify possible mechanisms of observed effects. A Sierran forest soil (pH 6.4) planted with Ponderosa pine seedling was exposed to simulated rain (pH 2.0, 3.0, 4.0 and 5.6) with ionic composition reflecting that found in northern California, corresponding to 15 cm of precipitation over a 12-week period. After exposure, the soils were collected in two samples (top 1 cm and 4 to 5 cm), which were assayed separately for respiration and enzyme activities (urease, phosphatase, dehydrogenase, and arylsulfatase). Changes in microbial activity were most significant in surface soils. Only the pH 2.0 input caused inhibition of both respiration and enzyme activities. The overall microbial response to the pH 3.0 and 4.0 acid regimes was one of stimulation, although the response of individual enzymes was more varied. In surface soils receiving the pH 3.0 input, for example, urease activity was unaffected while arylsulfatase and phosphatase were increased and decreased respectively.



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Therefore, individual microbial processes will have different sensitivities to acid rain. Although changes in C-availability in the exposed soils are documented, changes in the supply of N are evaluated as the major mechanism through which simulated acid rain affects soil microbial activity."

Lee, Edward H., Howard E. Heggestad, and Jesse H. Bennett. "Effects of Sulfur Dioxide Fumigation in Open-Top Field Chambers on Soil Acidification and Exchangeable Aluminum," Journal of Environmental Quality, Vol. 11, No. 1, 1982. 99-102.

"The effects of sulfur dioxide ($SO_2$) fumigation in open-top field chambers on soil pH and exchangeable Al were evaluated. Soil samples were taken from the surface 0-8 cm in plots where tomato plants were grown. The plants were exposed to treatments of varying concentrations of $SO_2$ in non-filtered air and C-filtered air. A high linear correlation was found between $SO_2$ exposure concentration and soil $SO_4$-S levels at the end of the fumigation period (r=0.95). Exchangeable Al was markedly increased at pH values below 5.5. The highest $SO_2$ exposure dose caused exchangeable Al in the surface soil to be increased more than tenfold from 0.64 to 6.53 percent of the total cation exchange capacity. Long term $SO_2$ exposure appears to possess the potential to induce Al phytotoxicity only when soil pH is reduced to below pH 5.0."

Linzon, S. N. and P. J. Temple. "Soil Resampling and pH Measurements After an 18-year Period in Ontario," Ecological Impacts of Acid Precipitation, Proceedings of an International Conference, Sandefjord, Norway, March 11-14, 1980. Ed. D. Drablos and A. Tollan. SNSF Project, Oslo, Norway, October 1980. 176-177.

Soil samples were collected from the same areas, soil types, and horizons in Ontario in 1978 as in 1960. Measurements of pH in 1960 were found to be esentially unchanged in 1978. Among the tentative conclusions are: (1) Soils already acidified are not readily altered by acidic precipitation; (2) Drainage through these soils to rivers and lakes is likely to be about as acidic as the incoming precipitation, not more so; (3) Lakes in such areas (acid soil drainage basins), if sensitive to acid precipitation, are thus threatened not by the acidic soils surrounding them, but by the acidity of the precipitation itself, whether falling on the lake directly or coming in from the drainage basin by stream or groundwater; (4) Soils sensitive to acid precipitation (in terms of the rainfall making the soil more acid) are thus likely to be neither the acid soils nor those well buffered, but soils such as a non-calcareous sandy soil with a pH over 6. These conclusions are consistent with those of Wiklander in Sweden.



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Lowendorf, Henry S., Ana Maria Baya, and Martin Alexander. "Survival of Rhizobium in Acid Soils," Applied and Environmental Microbiology, Vol. 42, No. 6, December 1981. 951-957.

"Legumes are major sources of protein and energy for both humans and domestic animals, and the legume-Rhizobium symbiosis is now the most widely managed agricultural system for biological nitrogen fixation. A large portion of the potentially arable land in many regions of the world is acidic, and soil acidity is frequently a major constraint for the cultivation of leguminous crops. Understanding the behavior of Rhizobium in acid soils is therefore important for successful nodulation, development of the nitrogen-fixing symbiosis, and ultimately crop yield. Concern with the influence of low pH on Rhizobium is not new...."

"R. meliloti seems to be the species of Rhizobium most sensitive to soil acidity. However,....little has been reported about the survival of several economically important species of Rhizobium in acid soils. Hence, studies were initiated to compare the survival of R. meliloti, R. phaseoli, and a strain of cowpea Rhizobia in acid and limed soils and to determine how survival in soil might be related to growth in culture..."

"The results show the striking differences in survival among R. phaseoli, R. meliloti, and the cowpea Rhizobium in acid soils. The number of R. phaseoli surviving in sterile soils declined progressively as the pH declined, whereas the cowpea strain was tolerant to a wide range of pH in sterile soil. Because R. phaseoli was able to grow in culture at pH 4.4 but exhibited increasingly poor survival in sterile soils of decreasing pH above 4.4, it appears that abiotic factors other than simply soil acidity limit the ability of this organism to survive....The cowpea strain not only was insensitive to changes in soil pH, but it maintained a relatively stable large population is nonsterile soils as compared with other strains used in this study...."

"The differences in behavior among strains of one species suggest that sufficient genetic variability exists to warrant further search for strains with good survivability."

"These results confirm the findings of Tuzimura et al. that populations of Rhizobium are influenced in complicated ways by soil and plants and that species and strains of Rhizobium behave differently. More must be learned about the interaction of these factors if we are successfully to predict the persistence of Rhizobia in natural ecosystems."

Reuss, John O. "Simulation of Soil Nutrient Losses Resulting from Rainfall Acidity," Ecological Modelling, Vol. 11, No. 1, October 1980. 15-38.

"This paper describes a simulation model that provides a quantitative system utilizing established relationships from soil chemistry to predict the most



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likely effect of rainfall acidity on the leaching of cations from non-calcareous soils....Due to the limited number of ions considered and numerous simplifying assumptions, the model is regarded as preliminary.... The model is strictly abiotic and does not take into account biological processes of any type. It could be very logically used, however, as a module in a more comprehensive ecosystem nutrient cycling model..."

"The following specific conclusions were arrived at by a first generation model of this type that applies only to noncalcareous soils. The initial results of these investigations indicate that significant acidification and depletion of bases could occur over a period of a few decades if rainfall inputs are consistently acidified to pH 4.0 with sulfuric acid.... However, the predictions given by the model show clearly the effect of seasonal precipitation-evaporation relationships of a magnitude about 2.5 times the overall change that would be expected to occur in a decade in response to pH 4.0 rainfall. Experiments that depend on soil water extract or suspension pH measurements to evaluate the effect of acid rainfall inputs would be subject to serious errors due to these fluctuations...."

"The output of this model confirms that soils well supplied with bases are most susceptible to base loss and that, as base saturation and lime potential fall to low levels, acid precipitation causes leaching of hydrogen and aluminum ions rather than bases..."

Strayer, Richard F. and Martin Alexander. "Effects of Simulated Acid Rain on Glucose Mineralization and Some Physicochemical Properties of Forest Soils," Journal of Environmental Quality, Vol. 10, No. 4, October-December 1981. 460-465.

"To study the effects of acid rain, samples of forest soils were exposed to a continuous application of 100 cm of simulated acid rain (pH 3.2-4.1) at 5 cm/hour, or to intermittent 1-hour applications of 5 cm of simulated acid rain three times per week for 7 weeks. The major effects of the simulated acid rain were localized at the top of the soil and included lower pH values and glucose mineralization rates, and higher exchangeable Al and total and exchange acidity. The acidity penetrated further in the more acid soils....Glucose mineralization in the test soils (pH values of 4.4-7.1) was inhibited by the continuous exposure to simulated acid rain at pH 3.2 but not at pH 4.1. The extent of inhibition depended on the soil and the initial glucose concentration. Exposure of one soil to 7 weeks of intermittent applications of simulated acid rain at pH 3.2 reduced the mineralization rate at the three glucose concentrations tested. These data suggest that acid rain may have a significant impact on microbial activity..."

"The rates of acid input in both the acute and chronic exposures were greater than those observed in the field. However, an assessment of effects using natural rates of acid input would require long periods of time, especially if the microbial responses to the precipitation of a



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single year are small, and hence these higher application rates were chosen deliberately. Such an approach is common in toxicology in order to predict a possible influence of toxicants in a short period of time. The major effects of short-term exposures to simulated acid precipitation were localized at the top of the soil...."

"An acute exposure regime can be used to determine which soils and microbial activities are potentially vulnerable to acid rain. However, acute exposure to acid precipitation may inhibit microorganisms only during the initial exposure. Because the stressed microorganisms may eventually be replaced by variants or other species that are resistant to low pH or the toxic circumstances, the possibilty of adaption to tolerance of stresses associated with soil acidity must be considered."

"In the intermittent exposures to the simulated acid rain in a 7-week period, a more gradual acidification of soil took place, and thus there was a chance for adaptation to occur. Some acclimation was evident because the ratios of the mineralization rates were considerably higher than the ratios calculated for the acute exposure experiment using the same soil; however, the acid rain still caused a significant reduction in heterotrophic activity in the intermittently treated soil. Whether this inhibition occurs in soils exposed to acid rain for time periods longer than 7 weeks is unknown, and further evaluations are necessary to determine if adapation to acid soil conditions occurs with prolonged exposure to acid precipitation...."

Wainwright, M. "Effect of Exposure to Atmospheric Pollution on Microbial Activity in Soil," Plant and Soil, Vol. 55, 1980. 199-204.

"Surface samples of a brown earth soil, showing signs of podzolization, were transferred from an unpolluted woodland site and exposed to heavy atmospheric pollution for a period of one year. Although exposure resulted in a decrease in soil pH from 4.2 to 3.7, no significant changes in microbial numbers, nitrification rate, respiration rate, solubilization of insoluble phosphate, or the activity of a range of soil enzymes occurred. The rate of ammonification was, however, higher in the exposed than the control soil."

"Microbial activity in the unpolluted soil was not, therefore, substantially impaired by exposure to heavy atmospheric pollution, despite the fact that the pH of the soil was reduced."



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## Effects on Trees and Forests

### Surveys and reviews

Abrahamsen, Gunnar. "Acid Precipitation, Plant Nutrients and Forest Growth," Ecological Impacts of Acid Precipitation, Proceedings of an International Conference, Sandefjord, Norway, March 11-14, 1980. Ed. D. Drablos and A. Tollan. SNSF Project, Oslo, Norway, October 1980. 58-63.

It is not possible to make a generalization about a common effect of acid precipitation on all or even most forests. Since acid precipitation typically deposits both nitrogen and sulfur upon the forest, the long-term impacts of these macronutrients may be viewed as a special case of applying incomplete fertilizers. The effect on forest growth will depend on the type of forest soil which exists, specifically which of the major nutrients--nitrogen, sulfur, potassium, magnesium, or phosphorus--is the limiting nutrient, in shortest relative supply. For example, in a forest area where nitrogen is deficient, the impact of added nitrogen from acid rain may be favorable on tree growth in the short-run, but unfavorable in the long-run, as other nutrients may used up or leached, and thus become severely limiting.

Abrahamsen, Gunnar. "Impact of Atmospheric Sulfur Deposition on Forest Ecosystems," Atmospheric Sulfur Deposition: Environmental Impact and Health Effects. Ed. D. Shriner, C. Richmond, and S. Lindberg. Proceedings of the Second Life Sciences Symposium, Gatlinburg, Tennessee, October 14-18, 1979. Ann Arbor Science, Ann Arbor, Michigan, 1980. 397-416.

"Results from experiments in coniferous forests supplied with artificial rain of varying acidity are discussed....Artificial rain with pH at 3 and below has significantly increased the net leaching of potassium, calcium, and magnesium. As a consequence, the base saturation and soil pH have decreased. There are strong indications that the present acidity of precipitation has also reduced the concentration of exchangeable metal cations in the soil. A significant net leaching of ammonium and nitrate has been found in the most acidified plots. Variations in soil chemical properties have not significantly influenced the concentrations of most nutrient elements in the needles. In one experiment the foliar concentration of nitrogen was temporarily enhanced. This was most likely the reason for a slight increase in the tree growth."



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Abrahamsen, Gunnar, Richard Horntvedt and Bjorn Tveite. "Impacts of Acid Precipitation on Coniferous Forest Ecosystems," Proceedings of the First International Symposium on Acid Precipitation and the Forest Ecosystem, Columbus, Ohio, May 12-15, 1975. Ed. L. S. Dochinger and T. A. Seliga. Forest Service General Technical Report NE-23, Forest Service, USDA, 1976. 991-1009.

Current results of ongoing studies in Norway on the impact of acid precipitation and dry deposits on coniferous forest ecosystems are summarized. The studies include investigations on soil, leaching from tree crowns, germination, establishment of seedlings, and tree ring analysis. Experiments revealed that the application of artificial acid rain to a podzol soil increased humus acidity and decreased base saturation. "[D]ecomposition of pine needles was not affected by any acid 'rain' treatment." Liming decreased decomposition and increased nitrification. "The soil enchytraeid....fauna were not significantly affected by the acidification. Germination of spruce seeds....was negatively affected when soil pH was 4.0 or lower. Seedling establishment was even more sensitive....Deposition of sulphuric acid beneath spruce and pine is approximately two times the deposition in open terrain....Increased acidity of the rain seems to increase the leaching of cations from the tree crowns....No effect that can be related to acid precipitation has yet been detected on diameter growth."

Andersson, Folke, Torbjorn Fagerstrom, and S. Ingvar Nilsson. "Forest Ecosystem Responses to Acid Deposition--Hydrogen Ion Budget and Nitrogen/Tree Growth Model Approaches," Effects of Acid Precipitation on Terrestrial Ecosystems. Ed. T. C. Hutchinson and M. Havas. Proceedings of the NATO Conference on Effects of Acid Precipitation on Vegetation and Soils, held in Toronto, Canada, May 21-27, 1978. Plenum Press, New York, 1980. 319-334.

The hydrogen ion budget and the nitrogen dependent tree growth model are two analytical techniques to test hypotheses about the effects of acidification on forest systems. Atmospheric deposition of varying kinds and composition can perturb the many variables in a forest ecosystem in numerous ways. Few conclusions can yet be drawn, although, as a rule, the ecosystem tends to dampen the perturbation. Tree ring growth is not necessarily the best or the only variable to be evaluated. To be able to better assess the extent of soil acidification, a better definition of soil "sensitivity" to acidity needs to be developed. This defintion of sensitivity needs to be specific in both chemical and biological terms.

Bormann, F. H. "The Effects of Air Pollution on the New England Landscape," Ambio, Vol. 11, No. 6, 1982. 338-346.

"The ecosystems of New England are being exposed to an unprecedented and increasing amount of air pollution. It is a critical task to determine the



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effects of this stress, but it is extremely difficult to precisely estimate the damage. Regional air pollution is not simply acid rain, but a mix of photooxidants, gases, trace metals, inorganic substances, and man-made organic chemicals. This mixture makes it exceedingly hard to analyze the effects of single pollutants. Estimation of the effects of air pollution is further complicated by synergism, neutral or even beneficial agents, and by potential gradual accumulation of damage. Natural ecosystems such as forests, fields, streams and lakes are difficult media in which to measure the effects of pollution because of size, seasonal and yearly variation, development and other subtle changes...."

"Despite these difficulties, ecologists have shown that forest ecosystems respond to increasingly severe pollution in a highly repeatable pattern. The pattern of decline of a forest ecosystem under increasingly severe air pollution stress, either chronic or episodic, can be thought of as a series of stages leading to ecosystem collapse...."

"Laboratory, greenhouse, and field experiments with simulated acid rain have shown numerous effects on both crop and wild plants including the leaching of nutrients from leaves, increased potential for infection by bacterial and fungal pathogens, synergistic effects of sulfur dioxide and ozone in damaging leaves, premature senescence of leaves and reduction in the establishment of tree seedlings. Experimental work has also shown effects on soils, such as increased leaching of nutrients, acidification, and increases in availability of toxic metals. Acidification is also known to affect soil processes like nitrogen fixation and decomposition. Despite this impressive array of specific biological and soil effects of simulated acid rain, reliable evidence of acid rain resulting in economic damage to crops or forest trees is scanty. Nevertheless, we know that certain processes accelerated by acid rain, like foliar and soil leaching and increased availability of toxic aluminum in some soils, are underway. In some ecosystems, long-term effects of this type could be serious...."

"In sum, the findings suggest that productivity (photosynthesis) of natural ecosystems covering large areas in the eastern United States may be depressed by concentrations of ozone that exist today....The photosynthesis fixation of solar energy by plants is the cornerstone of all ecosystem activities. Consequently, chronic depression of photosynthesis raises questions of fundamental importance about indirect effects of air pollution on ecosystem function....If air pollution continues at current levels for a few decades, the likely results in New England include a decline in genetic diversity, loss of regional landscape productivity, diminishment of the economic significance of many plant and animal species, unacceptable degradation of valuable forest, stream and lake ecosystems, and significant loss of biotic regulation of biogeochemical cycles...."



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Cogbill, Charles V. "The Effects of Acid Precipitation on Tree Growth in Eastern North America," Proceedings of the First International Symposium on Acid Precipitation and the Forest Ecosystem, Columbus, Ohio, May 12-15, 1975. Ed. L. S. Dochinger and T. A. Seliga. Forest Service General Technical Report NE-23. Forest Service, USDA, 1976. 1027-1032.

Tree ring analysis of forest tree growth was used to assess the effect of acid precipitation. "The pattern and historical trends of acid precipitation deposition are compared with growth trends from mature forest stands in New Hampshire and Tennessee....No regional synchronized decrease in radial increment growth was evident in the two mature stands studied....Despite different acid precipitation regimes, these two stands displayed similar growth patterns. Slight recent decreases in basal area increment in the mature stands were neither dramatic nor without precedent, but acid precipitation cannot be eliminated as their cause. Weather, stand dynamics, and determination error are probable contributory causes. [D]ue to the unknown initiatic date of acid precipitation and to the large variance of tree growth estimates with no break point, a correlation of forest growth and acid precipitation cannot be established at the present time."

Council for Agricultural Science and Technology (CAST). Acid Precipitation in Relation to Agriculture, Forestry, and Aquatic Biology, Report of the CAST Multidisciplinary Task Force on Acid Precipitation. CAST Report No. 100, June 1984. Ames, Iowa.

"Forested soils generally do not receive limestone or fertilizers. Thus, chronic losses of nutrients over several decades under the influence of acid deposition could lead to nutrient deficiencies in some soils. No such deficiencies, however, have been demonstrated. Natural acidification processes in forest soils produce the same end effects as those attributed by some to acid deposition. The relative importance of the various internal and external sources of acidity has not been settled scientifically and will require further research. It is unlikely that the additional acidity supplied from strongly acid precipitation in a humid region would cause a significant increase in acidity in many soils or a significant alteration in microbial processes in the soils.

"There are no research results indicating that acid precipitation has a direct damaging effect on forest vegetation at pH values of precipitation occurring in the United States. The possibility that significant changes in species composition and forest productivity might result over a period of a few decades from influences of acid deposition on seed production, germination, and seedling behavior is now under investigation.

"Although the recent dieback of forests in Scandinavia, Germany, and the northeastern United States has been attributed in part by some researchers to acid deposition, the connection is not clear. Other factors seem to have been involved, and the importance of acid deposition is not yet known."



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Cowling, Ellis B. "Acid Rain in Perspective: The Path from Research to Public Policy," Acid Precipitation: The North American Challenge. Proceedings of a conference held October 25-28, 1982 in Burlington, Vermont. Soil Conservation Society of America, Ankeny, Iowa, 1983. 2-1 to 2-30.

"The major known detrimental effects of ambient acid deposition are restricted to certain sensitive aquatic ecosystem...."

"The major sensitive regions in North America....usually are recently glaciated, with large areas of exposed granitic (crystalline) and other noncalcareous bedrock and thin soils that are low in acid-neutralizing and cation-exchange capacity...."

"At present there is no compelling evidence that the effects of ambient acid deposition on terrestrial ecosystems are more detrimental than beneficial. Mainly on the basis of controlled exposures of crop plants and forest trees to simulated acid deposition, we have good reason to be suspicious, but no compelling evidence with which to conclude, that forest and agricultural ecosystems are presently being harmed by ambient acid deposition...."

"In various regions of North America, economic damage to forests and agricultural crops is occurring as the result of dry deposition of toxic gases. Ambient concentrations of ozone, sulfur dioxide, and oxides of nitrogen, acting alone or in combination, are causing important damage and decreases in yield of both crops and forests. For two major reasons this demonstrated harm to crops and forests by toxic gases should be considered both together with and separately from the well-demonstrated effects of acid deposition on aquatic ecosystems: (a) Sulfur and nitrogen oxides are the very same substances that serve as chemical precursors of atmospheric ozone and other photochemical oxidants, respirable particulate matter, atmospheric haze, and/or acid deposition; and (b) mixtures of ozone, sulfur dioxide, and nitrogen oxides, as well as mixtures of ozone and acid precipitation have been shown to induce greater harm to various plants than these pollutants acting alone...."

"Gaseous emissions of sulfur and nitrogen oxide from combustion of fossil fuels are the principal sources of acidifying substances...."

Einspahr, D. W. and M. L. Harder. "Acid Rain: Its Effects on the Paper Industry," TAPPI Journal, Vol. 64, No. 4, April 1981. 61-64.

The author discusses the results of a literature review focusing on acid rain impacts on forest growth. He uses information obtained in 20 completed studies. A number of researchers have attempted to document reduction in forest growth due to acid rain, but in most instances have not been successful. The lack of research findings which demonstrate reduced forest growth is attributed to the following: "(1) Acid rain modifies forest soils very slowly, and may have little or no effect on many soils;



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(2) Forest trees have low nutrient requirements; (3) Nitrogen, which is an important component of acid rain, is the element that most often improves growth; and (4) Relatively crude measurement techniques are available for measuring the long-term effects of acid rain."

Helvey, J. D., Samuel H. Kunkle, and David R. DeWalle. "Acid Precipitation: A Review," Journal of Soil and Water Conservation, May-June 1982. 143-148.

The authors base their review on 44 references. They conclude as follows:

"[S]ome scientists believe that acid precipitation is causing widespread degradation of both aquatic and terrestrial ecosystems. Others are not convinced that it is more than a localized problem....Not all atmospheric deposition in the northeastern United States is associated with rain and snow. Dry fallout (consisting of solid particles, aerosols, and gases, between precipitation events) is also an important process. Few reports have attempted to quantify dry fallout...."

"Certain tree species near smelters of factories can be killed by air pollution such as smoke and ash....One review of research presented the maximum pH of simulated acid precipitation that produced visible injury to the foliage of selected plants. In other studies, yellow birch developed foliar lesions and exhibited a reduction in growth rate at pH 3.1; hybrid poplar developed foliar lesions at pH 3.4. If these results are typical for forest vegetation, present levels of precipitation acidity probably are not directly harmful to forest vegetation...."

"Long-term effects of acid precipitation on the growth rates of vegetation and soil fertility are difficult to ascertain and will demand some very long-term research. One of the main topics under investigation is the effect of acid precipitation on the cuticular layer of leaves. There is concern that leaching of minerals from this layer will lead to injury of surface cells, plant water stress, and a reduction in photosynthesis...."

"One of the greatest concerns is how long a forest can continue to absorb acid impacts. Will certain forest ecosystems gradually approach some 'end point,' where they are poisoned to a level that permanently ruins productivity? Research has not progressed enough to permit long-term predictions on such acid precipitation impacts. Most scientists recognize that many questions about acid precipitation still exist. Some feel action is necessary to reduce sulfate and nitrate emissions soon; there is no waiting until more answers are available, they say...."

"Other scientists view the concern about acid precipitation as premature. They see the concern as an overextrapolation of isolated cases from certain northern high mountain or pristine lake sites. They agree that the precipitation is acidic, but they are not sure if the problem is increasing or is significant beyond a few selected zones."



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Johnson, Arthur H. and Thomas G. Siccama. "Acid Deposition and Forest Decline," Environmental Science and Technology, Vol. 17, No. 7, July 1983. 294A-305A.

"Over the past 15-20 years, red spruce (Picea rubens Sarg.) in the high elevation forests of New York, Vermont, and New Hampshire has shown marked dieback and a very large reduction in basal area and density. A number of studies have been conduc , but none have revealed any obvious causes for the widespread mortality. The decline of red spruce has characteristics of a stress-related disease...."

"The key question to be resolved is: Does the forest dieback represent an early phase of pollution-induced ecosystem destabilization that will lead to essentially permanent changes (for example, changes in species composition or reduced productivity), or is the dieback a relatively short-term periodic phenomemon that occurs naturally in ecosystems that are stable when viewed over longer time spans?"....

"The location, topography, and other characteristics of the high-elevation forests of eastern North America cause them to be receptors of high levels of acid deposition and airborne trace metals. We contend that no other major forested areas in the U.S. are subjected to such intensely acid cloud moisture, such heavy acid deposition, and such high rates of trace-metal deposition. The vulnerability of these forests to the pollutants has not been documented, but because of the spruce decline it is indeed reasonable to suspect vulnerability. In reviewing the data currently available, we find several possible pathways by which acid deposition could contribute to spruce mortality, but at this time none of these pathways [is] supported by convincing evidence. The framework for aluminum toxicity proposed by Ulrich is not consistent with the data we have generated. On the other hand, we believe that the evidence regarding a triggering effect of drought is substantiated by our data and those of others, but we do not know whether drought is sufficient to cause the dieback and decline or whether an additional stress from pollution is involved."

"In viewing the spruce dieback and decline as a stress-related syndrome, we suggest the possibility of multiple stresses. Drought followed by infection by secondary organisms appears likely. Conceivably, acid deposition could enhance drought stress or vice versa. The interaction of acid deposition and secondary pathogens is also a possibility that warrants investigation. The prospects for ecosystem destabilization are difficult to assess in light of the available data. To adequately assess the possibility that the high-elevation forest ecosystems may be 'unraveling' in response to current levels of pollutant inputs, more information is needed on population dynamics, nutrient cycling rates, nutrient pool sizes, and aluminum biogeochemistry."



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Johnson, Dale W., Daniel D. Richter, Helga Van Miegrot, and Dale W. Cole. "Contributions of Acid Deposition and Natural Processes to Cation Leaching from Forest Soils: A Review," Journal of the Air Pollution Control Association, Vol. 33, No. 11, November 1983. 1036-41.

"Methods of quantifying the roles of atmospheric acid inputs and internal acid generation by carbonic, organic, and nitric acids are illustrated by reviewing data sets from several intensively studied sites in North America. Some of the sites (tropical, temperate deciduous, and temperate coniferous) received acid precipitation whereas others (northern and subalpine) did not. Natural leaching by carbonic acid dominated soil leaching in the tropical and temperate coniferous sites, nitric acid (caused by nitrification) dominated leaching in an N-fixing temperate deciduous site, and organic acids dominated surface soil leaching in the subalpine site and contributed to leaching of surface soils in several other sites."

"Only at the temperate deciduous sites did atmospheric acid input play a major role in soil leaching. In no case, however, are the annual net losses of cations regarded as alarming as compared to soil exhangeable cation capital. These results were used to illustrate the methods of quantifying the effects of atmospheric inputs and internal processes on soil leaching rates, not to draw broad generalizations as to acid rain effects on soils. However, there are predictable patterns in natural soil leaching processes which relate to climate, soil properties, and vegetation that may help in predicting the relative importances of natural vs. atmospheric acid inputs to soil leaching...."

Johnson, Dale W., John Turner, and J. M. Kelly. "The Effects of Acid Rain on Forest Nutrient Status," Water Resources Research, Vol. 18, No. 3, June 1982. 449-461.

"The effects of acidic atmospheric inputs on forest nutrient status must be assessed within the context of natural, internal acid production by carbonic and organic acids as well as the nutrient inputs and drains by management practices such as harvesting, fire, and fertilization. In all cases the anion associated with acid inputs must be mobile in the soil if leaching is to occur; immobilization of anions can effectively prevent cation leaching. Soil acidification will occur only if the often substantial buffering capacity of the soil in question is exceeded by acid inputs and if cation weathering from primary minerals is insufficient to offset cation losses by leaching. Such circumstances are rare but certainly could occur in theory, at least, given sufficiently large acid inputs on poorly buffered soils."

"Soils most sensitive to change are thought to be those of moderately acid pH and low cation exchange capacity. Neither very acid soils nor neutral, highly buffered soils are sensitive to acidification by acid rain. Given extremely high acid inputs, acid rain can cause temporary increases in nitrogen mineralization and nitrification as well as aluminum mobilization in soils. While temporary increases in nitrogen availability can cause



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increased forest growth in nitrogen-deficient forests, increased aluminum availability can cause toxic reactions in tree roots. Little is known about tree aluminum toxicity levels as yet, however."

"It must be emphasized that assessment of acid rain effects is a problem of quantification. Given sufficiently high inputs on sensitive sites, negative effects of acid rain must occur, as is true of inputs of any substance, including $H_2O$. Acid rain inputs of sufficient magnitude to cause acute effects, such as growth increase due to nitrogen mobilization or growth decrease due to aluminum mobilization, are apparently very rare under ambient field conditions. Long-term effects on forest nutrient status can be either beneficial or adverse, depending on site nutrient status, silvicultural practices, and amount of atmospheric inputs."

Mayer, Robert and Bernhard Ulrich. "Acidity of Precipitation as Influenced by the Filtering of Atmospheric Sulphur and Nitrogen Compounds--Its Role in the Element Balance and Effect on Soil," Water, Air, and Soil Pollution, Vol. 7, 1977. 409-416.

"Acidity of throughfall precipitation is increased by the filtering of S and N from the atmosphere by trees. An element balance for a beech forest is given. As a consequence of acidification the soil chemical conditions are changed in a way that plants rooting close to the soil surface are affected. Losses of nutrients may pose a problem in forest plant nutrition in the near future in Central European forests on light or medium textured acid soils."....

"The element balance data allow one to draw some conclusions regarding the effect of acidity of precipitation on the forest ecosystem: The buffering of protons, and to a minor extent accumulation of iron in the mineral soil, is balanced by the loss of aluminum, manganese, and, to a smaller extent, potassium. calcium, and magnesium. This is possible by the weathering of silicates, or, as in the case of potassium, calcium, magnesium, by desorption from the exchangeable fraction. These processes definitely change the soil chemical conditions in the uppermost 1 to 2 cm of the soil. While tree growth is probably not affected by the acidification of this layer, a disturbance of all plants rooting very close to the soil surface, as for example, germinating plants, is to be expected."

"Ulrich and Khanna (1968) have shown in which way this could happen: In a germination experiment with oats they found evidence that the damage of plants grown on soils with pH around 3 or lower was due to an inundation with aluminum and iron, and perhaps manganese. The high concentration of these elements in the soil solution at low pH led to a blocking of the phosphate transport from the seeds to the shoots. This process may be a sound explanation for the difficulties met in recent years in the natural reproduction of beech in Germany. Another effect of the acidity of precipitation is probably the accumulation of sulfur in the soil, which becomes evident from the element balance. The question in what form sulphate is



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accumulated is still under study....If we keep in mind that the acidification is effective mainly in the top 1 to 2 cm of the soil, this means an annual loss of about 1 percent of the total clay and plagioclase of loess soil. From this reasoning a manmade podzolization of the A-horizons seems possible. Finally the acidification of the soil and the associated loss of magnesium may become a problem in the supply of this nutrient element in the near future. A great number of recent leaf and needle analyses point to this direction."

McLaughlin, S. B., T. J. Blasing, L. K. Mann, and D. N. Duvick. "Effects of Acid Rain and Gaseous Pollutants on Forest Productivity: A Regional Scale Approach," Journal of the Air Pollution Control Association, Vol. 33, No. 11, November 1983. 1042-1049.

"This paper describes the rationale, methodology, and some preliminary results of a large regional scale study designed to characterize and quantify forest growth impacts attributable to atmospheric stress from both gaseous pollutants and acid rainfall. This research employs a variety of dendroecological techniques to examine the influence of climate factors, tree age, soil type competition, and air pollution on tree growth. This broadly collaborative project involves twelve government and university research stations working with a common experimental protocol to examine $\geq$ 50 year ring-width series from approximately 6000 trees distributed over an area extending from Maine to North Carolina and as far west as Missouri."

"Principal objectives of this research are to determine whether a systematic pattern of decreasing forest growth has occurred, to define its temporal, spatial, and quantitative characteristics, to determine its relationship to differences in soil quality and tree species, and to evaluate its correlation with present and past indices of atmospheric deposition."....

"Tree ring measurements have been used to successfully document changing growth rates of forest trees exposed to many different types and sources of air pollution. These have included fluorides from phosphate reduction plants, $SO_2$ from smelters and sulfite reduction plant, and combinations of $SO_2$ and $NO_2$ from a munitions plant. Additional studies in areas where regional elevation of gaseous pollutants, principally ozone, was occurring, have documented reduced radial increments in conifers. In both cases ozone damage was indicated by high ozone levels, needle symptom expression characteristic of ozone damage, and a characteristic decline in vigor of most obviously affected trees."....

"A common feature of all of the studies near point sources, however, has been the ability of investigators to use either variations in emissions levels over time or distance from a primary source as independent variables against which to evaluate tree growth effects. Cause and effects can be more clearly evaluated under these conditions than in the more regionally important modern day case where the major focus of concern is changes in productivity of forests chronically exposed to multiple pollutants, including both gaseous pollutants and acid rain."



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"Where the emphasis is on potentially subtle regional scale effects occurring over long time intervals, the challenges of separating natural from anthropogenic influences on the growth record are greatly magnified. This problem has been most acutely emphasized in recent efforts to document the effect of acid rain on forest productivity. Acid rain is a regional scale phenomenon which is still poorly understood with respect to both its effects on forested landscapes and the historical sequence by which present deposition patterns have emerged."

McLaughlin, S. B., D. J. Raynal, A. H. Johnson, and S. E. Lindberg. "Forests" section of "Effects on Vegetation" chapter, The Acidic Deposition Phenomenon and Its Effects: Critical Assessment Review Papers, Volume II, Effects Sciences. Eds. Aubrey P. Altshuller and Rick A. Linthurst. EPA Report 600/8-83-016BF, Office of Research and Development, U. S. Environmental Protection Agency, Washington, D. C., July 1984. 3-26 to 3-41.

[From the Preface to Vols. I and II: "The document's original charge was to prepare 'a comprehensive document which lays out the state of our knowledge with regard to precursor emissions, pollutant transformation to acidic compounds, pollutant transport, pollutant deposition and the effects (both measured and potential) of acidic deposition.'" Volume I concerns the atmospheric sciences, while Volume II (as noted above) covers the effects sciences. More than 50 scientists contributed to the report.]

"Summary-
At present there is no proof that acid deposition is currently limiting growth of forests in either Europe or the United States. From field studies of mature forest trees it is apparent that altered growth patterns of principally coniferous species examined to date have occurred in recent decades in many areas of the northeastern United States and in some areas of Europe with high atmospheric deposition levels. Recent increases in mortality of red spruce in the northeastern United States and Norway spruce and beech in Europe add further to the concern that forests are undergoing significant adverse change; however, no clear link has been established between these changes and anthropogenic pollutants, particularly acidic rainfall. This must be presently viewed from the perspective of two possible hypotheses: (1) Recent changes are purely circumstantial and not in any way linked to acid precipitation; or (2) we have not yet adequately studied a very complex association in which multiple and interactive factors may be involved and responses may be subtle and chronic."

"It is too early to conclude that acidic deposition has not nor will not affect forest productivity. Irrigation studies with seedlings and young trees provide no indication for immediate alarm, but they are difficult to interpret because of potential artifacts of experimental protocols. Detecting responses of mature forest trees is made difficult by the complexities of competition, climate, and site factors, the potential interactions between acid precipitation, gaseous pollutants, and trace metals, and the lack of control-or-unattended sites with which acid precipitation impacted



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sites can be compared. Although the task of assessing potential impacts of forest productivity will assuredly be difficult, the potential economic and ecological consequences of even subtle changes in forest growth over large regions dictates that it should be attempted."

Miller, H. G. "Throughfall, Stemflow, Crown Leaching and Wet Deposition," Methods for Studying Acid Precipitation in Forest Ecosystems: Definitions and Research Requirements. Ed. I. A. Nicholson, I. S. Paterson, and F. T. Last. Proceedings of a workshop held in Edinburgh, 19-23 September 1977, sponsored by the Natural Environmental Research Council, Institute of Terrestrial Ecology, Cambridge, England, 1980. 29-30.

The author discusses ecological research methods used in assessing acid precipitation in plant ecosystems. Sampling intensity and design of gauge are important in acid rain related measurements of gross precipitation, throughfall, and plant stemflow. Directions for future research needs are provided for separating crown leaching from rain input, factors controlling leaching of conifer needles, and processes of internal cycling of nutrients in trees under field conditions.

Miller, Hugh G. and John D. Miller. "Collection and Retention of Atmospheric Pollutants by Vegetation," Ecological Impacts of Acid Precipitation, Proceedings of an International Conference, Sandefjord, Norway, March 11-14, 1980. Ed. D. Drablos and A. Tollan. SNSF Project, Oslo, Norway, October 1980. 33-40.

"As forests are particularly effective at scavenging and retaining atmospheric elements, it follows that they would be peculiarly at risk from atmospheric pollutants. In remote parts of the mountains of New England, Reiners et. al. found levels of lead in organic matter comparable with those in many heavily traveled roadsides; the vertical distribution of this lead indicated that levels were still rising. As there was a greater accumulation in fir forests than in tundra, and as an earlier study had shown enhanced lead input beneath artificial foliage, the filtering effect was clearly the amplifying factor. Even remote regions, therefore, may be at risk from atmospheric pollution if they are forest covered. This risk, as Likens and Bormann pointed out, will continue to worsen as an increasing amount of the industrial emissions of acid-promoting substances, and of heavy metals, are injected high into the atmosphere, leading to wide dispersion and the eventual possibility of incorporation into the normal processes of forest soil enrichment."....

"The efficient collection and retention of atmospheric nutrients is an important ecological mechanism, permitting trees to thrive on poor soils and enabling eventual succession with more nutrient demanding species. A consequence, however, is that forests will be peculiarly sensitive to atmospheric pollution."



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National Research Council, Committee on Medical and Biologic Effects of Environmental Pollutants. Ozone and Other Photochemical Oxidants, National Academy of Sciences Publishing Office, Washington, D. C., 1977.

The Executive Summary of the report contains a sub-section on "Effects on Plants, Ecosystems, and Materials." An excerpt from this sub-section follows:

"There is convincing evidence of large-scale damage to natural ecosystems in regions downwind from Los Angeles. The injury to the mixed-conifer stands of the San Bernardino National Forest began in the early 1940's and is well advanced. A similar problem is developing in the forests of the southern Sierra Nevada. Both direct and indirect effects have been observed on most components of the forest ecosystem, including producers, consumers, and decomposers. These effects are the results of reactions in the Los Angeles urban plume, which generate oxidants as the pollutants are transported downwind. Other cities of the western United States--namely, Salt Lake City and Denver, where basin-mountain terrain is contiguous--may show similar injury to forest ecosystems as their oxidant air pollution problems grow."

Office of Technology Assessment, Congress of the United States. Acid Rain and Transported Air Pollutants: Implications for Public Policy. Report OTA-O-204, June 1984. Washington, D.C.

The principal objective of this report is to present and analyze policy options for dealing with the acid rain and air pollution issues. Much of the report is devoted to policy analysis. However, in a portion of the Summary, in Chapter 3, and in Appendix B extensive material dealing with effects of these pollutants is also presented, including agricultural effects.

With respect to forests, the OTA report summarizes its findings as follows: "Broad forested areas subjected to elevated levels of acid deposition, ozone, or both have been marked by declining productivity and dying trees, although it is uncertain how much of this is due to airborne pollutants. [There are] significant growth declines in several tree species beginning about 1960 throughout the East from Vermont to Tennessee. Acid deposition, ozone, heavy-metal deposition, drought, severe winters, or a combination of these stresses are possible causes under investigation."

"Acid deposition might be harming trees in two ways: Either directly (for example, by removing nutrients from leaves), or indirectly, by altering the soils on which trees grow. If acid deposition harms trees directly, much of the forested area of the Eastern United States is at risk, with the greatest risk in high elevation areas where deposition is often greatest. If acid deposition affects forest soils, forests growing on nutrient-poor, naturally acidic soils are of greatest concern. This study estimated that such soils cover about 15 to 20 percent of the land area of the Eastern



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United States, primarily parts of New England, the Upper Midwest, and the South. Acid deposition might be stripping such essential nutrients as calcium and magnesium from these soils, or releasing metals, such as aluminum, that are toxic to plants. Whether this nutrient loss or release of metals from the soil is large enough to affect forest productivity at current levels of acid deposition is unknown."

"A large area of U. S. forests is also exposed to elevated ozone concentrations. Ozone has been shown to damage tree foliage and reduce the growth rates of certain sensitive tree species. But its cumulative effect on forest productivity over the lifetime of trees--half a century or more--is difficult to predict."

Phillips, S. O., J. M. Skelly, and H. E. Burkhart. "Growth Fluctuation of Loblolly Pine Due to Periodic Air Pollution Levels: Interaction of Rainfall and Age," Phytopathology, Vol. 67, June 1977. 716-720.

"The inhibition of growth in forest trees due to the presence of several different air pollutants has been demonstrated [in prior research]. Several researchers have demonstrated that growth losses can occur without the presence of 'visible symptoms'....The 'hidden injury' theory of plant damage due to air pollution as developed by Stoklasa....in 1923 considered two points important to the analysis of growth loss: A reduction in the photosynthetic activity of the plants, and reduced growth and/or yield without symptom development."....

"Loblolly pine....was examined owing to its importance to the forest industry of Virginia and the southeastern United States....There were three distinct objectives of these investigations: (i) To determine what correlations, if any, existed between historic production levels of the RAAP [Radford Army Ammunition Plant--an emitter of oxides of nitrogen and sulfur dioxide] and the annual radial growth of loblolly pine; (ii) to evaluate what effect tree age and rainfall had upon correlations of growth and production levels; and (iii) to obtain and estimate of the growth impact of the sulfur dioxide-nitrogen oxides air pollution regime on loblolly pine within the RAAP."....

"These results indicate that loblolly pine trees planted within the RAAP may be undergoing an inhibition of growth which is proportional to the RAAP's production levels and which is influenced by tree age and rainfall. These results, therefore, conform to Stoklasa's....concept of invisible injury. It also is probable that some loblolly pine trees may exhibit a tolerance to the nitrogen oxides-sulfur dioxide air pollution regime at the RAAP. The conclusion that symptom expression is not a prerequisite for growth loss places severe restriction upon growth loss estimates utilizing symptoms for damage estimates. It, therefore, is highly possible that growth loss in forests subjected to low-level and long-term exposure to air pollutants may be occurring unnoticed and/or unevaluated."



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Postel, Sandra. Air Pollution, Acid Rain, and the Future of Forests. Worldwatch Paper 58, March 1984. Worldwatch Institute, Washington, D. C.

"A comprehensive look at worldwide forest damage reveals multiple pollutants--including acid-forming sulfates and nitrates, gaseous sulfur dioxide, ozone, and heavy metals--that acting alone or together place forests under severe stress. Needles and leaves yellow and drop prematurely from branches; tree crowns progressively thin, and, ultimately, trees die. Even trees that show no visible sign of damage may be declining in growth and productivity. Moreover, acid rain's tendency to leach nutrients from sensitive soils may undermine the health and productivity of forests long into the future. Taken together, these direct and indirect effects threaten not only future wood supplies but the integrity of whole ecosystems on which society depends."....

"Although scientists cannot yet fully explain how this forest destruction is occurring, air pollutants and acid rain are apparently stressing sensitive forests beyond their ability to cope. Weakened by air pollutants, acidic and impoverished soils, or toxic metals, trees lose their resistance to natural events such as drought, insect attacks, and frost. In some cases, the pollutants alone cause injury or growth declines. The mechanisms are complex and may take decades of additional research to fully understand. But this growing body of circumstantial evidence is one more telling sign that fossil-fuel combustion has ecological limits, and that society will pay a price for overstepping them."

Roberts, Leslie. "Is Acid Deposition Killing West German Forests?" BioScience, Vol. 33, No. 5, May 1983. 302-305.

"In 1981, in response to widespread public concern the (West German) Government convened a working group of Federal and State scientists under the auspices of the Federal Ministry of Food, Agriculture and Environment, the Federal Ministry of the Interior and the State commission for Emission Protection to investigate damage to West German forests. The following discussion is based on their report, Forest Damage Due to Air Pollution, released in November 1982."....

"The picture that emerges is one of combined, cumulative effects in which sulfur dioxide and its conversion products play a primary role. Weakened by this pollutant stress, trees are prone to damage from a variety of environmental factors, such as drought, frost, and wind. Many U.S. scientists are reluctant to draw conclusions about the role of acid deposition in forest damage, either in West Germany or the United States, since so little is known about its effects on vegetation. Though it may contribute, they speculate that, instead, drought is the primary cause of increasing forest damage. There is consensus, however, both here and in West Germany, that the causes are probably many, and the mechanisms are complex. Whichever cause is labeled primary, the fact remains that drought, frost, and other acts of nature will continue. Pollution is the only factor that can readily be controlled."



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Smith, William H. "Air Pollution: Effects on the Structure and Function of the Temperate Forest Ecosystem," Environmental Pollution, Vol. 6, 1974. 111-129.

"The nature of this [air pollution/forest ecosystem] relationship can be divided into three classes. Under conditions of low dosage--Class I relationship--the vegetation and soils of forest ecosystems presumably function as a very important sink for air contaminants. When exposed to intermediate dosage--Class II relationship--individual tree species or individual members of a given species may be adversely and subtly affected by nutrient stress, reduced photosynthetic or reproductive rate, predisposition to entomological or microbial stress, or direct disease induction. Exposure to high dosage--Class III relationship--may induce acute morbidity or mortality of specific trees."

"The ecosystem impact of these relationships would be very variable. In the Class I relationship, pollutants would be transferred from the atmospheric compartment to the biotic (organic) or available nutrient compartments. Depending on the nature of the pollutant, the ecosystem impact of this transfer could be undetectable (innocuous effect?) or stimulatory (fertilising effect). If the effect of air pollution exposure on some component of the ecosystem biota is inimical then a Class II relationship is established. The ecosystem impact in this case could include reduced productivity or biomass, shifts in species composition, increased secondary effects, such as insect outbreaks or disease epidemics, or increased morbidity and reduced vigour. The ecosystem impacts of Class II relationships are extraordinarily important because of their potentially widespread significance. In the presence of high air pollution dosage--Class III relationship--impact on the structure of the ecosystem may include basic changes in hydrology, nutrient cycling, erosion, microclimate and overall stability.

While these numerous ecosystem impacts, resulting from air pollution stress, have been identified, few have been quantified in the field. We are especially deficient in our ability generally to assess Class I and Class II relationships. This hiatus of knowledge is due to several factors in addition to the obvious difficulty of making accurate measurements of subtle processes in expansive and frequently remote forest ecosystems. Among the most important factors are: (1) The extraordinarily variable response different plant species and individuals within species have to individual air pollutants, (2) the strong controlling influence that local edaphic, topographical and meteorological conditions exert on plant response to air contaminants, (3) the fact that numerous tree species and most forest shrub and herb species have not been evaluated in regard to air pollutants, (4) the realisation that most of our data stem from studies with a very few pollutants reacted singly and that some gaseous and particulate contaminants and mixtures of pollutants have received little research attention, (5) that much of the research has been conducted employing air pollution dosages in considerable excess of ambient forest levels, and that (6) most of the investigations have been carried out under highly controlled--and hence artificial--environments.



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Smith, William H. Air Pollution and Forests: Interactions between Air Contaminants and Forest Ecosystems. Springer-Verlag/New York, Inc., 1981.

Interactions between air contaminants and forest ecosystems are divided into three classes, depending on pollutant dose. [See previous entry by the same author.] An intermediate pollutant dose (Class II relationship) is an exposure above an approximate "threshhold" level for a specified pollutant-tree combination which, when exceeded, tends to lead to specified symptoms of tree or forest plant damage. The author lists pollutant-tree threshhold combinations based on findings of many researchers. He lists threshold doses (by type of tree) for the following pollutants, which the author terms "major": Sulfur dioxide, nitrogen oxides, ozone, PAN, fluoride, and trace metals; and for the following other pollutants, which the author terms "minor": Acid rain (threshold amount pH 3.0 or less), ammonia, chlorine, ethylene, and hydrogen sulfide. Ecosystem response to a given dose varies widely with other influences, and the dose required to elicit a given response also varies with circumstances, so that the above threshhold combinations should be viewed as generalized, not site-specific guides to forest tree sensitivity.

The author cites numerous case studies which illustrate the Class II interaction. With respect to acid rain: "The data reviewed to support the hypothesis that acid precipitation accelerates leaching loss of nutrients from forest foliage are not convincing....Studies that have employed seedling trees subjected to artificially acidified rain have revealed a potential for foliar nutrient loss, but only at pH levels of 4.0 or less. In the presence of foliar damage to the cuticle occasioned by acid rain, nutrient loss from leaves could be substantial. The threshold for this damage, however, appears to be approximately pH 3 for numerous forest trees and this intensity of precipitation acidification is not widespread in natural environments at the present time."....The bulk of the current evidence, however, is consistent with the conclusion of Frink and Voigt (1976) that unless the acidity of precipitation increases substantially or the buffering capacity of forest soils declines significantly, acid rain influence will not quickly nor dramatically alter the productivity of most temperate forest soils."

The following is an additional example of a Class II interaction: "....[I]nvestigators studying the relationship between air pollutants and tree photosynthesis have primarily employed tree seedlings for research material and controlled environmental facilities for growth....Much of the seedling and sapling evidence suggests that the photosynthetic inhibition caused by sulfur dioxide and ozone is reversible if the pollutant stress is removed.... Almost all the studies report photosynthetic depression in the absence of, or at least prior to, the appearance of visible foliar symptoms. The evidence for air pollution-induced photosynthetic suppression in large trees in natural environments is extremely meager and fragile. The seedling-sapling evidence, however, demonstrates a threshold of effect that approaches ambient concentrations in numerous temperate environments."



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A further, related example is: "The only documentation of correlation of growth parameters of large trees growing under field conditions with ambient ozone levels has been provided by the comprehensive oxidant study conducted in the San Bernardino National Forest in California....An average 30-year old tree grown in contemporary air was estimated to reach 7.0 meters height, 19 centimeters diameter, and be capable of producing one log 1.8 meters long with a volume of 0.047 cubic meters. An average 30-year old tree grown in the absence of oxidants was estimated to be 9.1 meters height, 30.5 centimeters in diameter, and produce one log 4.9 meters long with a volume of 0.286 cubic meters."

"Atmospheric burdens of contaminants are generally of sufficient magnitude to cause Class III interactions only in those portions of forest ecosystems in the vicinity of major point sources of atmospheric contaminants.... The most important deficiency in our understanding of Class III relationships concerns oxidant influence on forest ecosystems. Oxides of nitrogen, ozone, and PAN are generated and released from....large urban complexes.... and as such are transported into surrounding forests in association with large air mass movements rather than in small, discrete plumes....[W]e have less than acceptable appreciation of the ability of ambient oxidants to cause acute morbidity and mortality in natural forests."

Ulrich, B. "A Concept of Forest Ecosystem Stability and of Acid Deposition as Driving Force for Destabilization," Effects of Accumulation of Air Pollutants in Forest Ecosystems. Ed. B. Ulrich and J. Pankrath. Proceedings of a workshop held at Gottingen, West Germany, May 16-18, 1982. D. Reidel Publishing Co., Dordrecht, Holland, 1983. 1-29.

"A theory is proposed which explains the acidification and alkalinization of soils, respectively, as consequence of the discoupling of the ion cycle in the ecosystem....A continuous input of acidity exceeding the rate of base cation release by silicate weathering within the root zone forces forest ecosystems from the stability ranges into the transition states (destabilization phases). The concept of stress and strain is used to deduce how acid deposition superimposes natural stress factors and may trigger forest damages connected with climatic extremes and pests."

Ulrich, B. "Production and Consumption of Hydrogen Ions in the Ecosphere," Effects of Acid Precipitation on Terrestrial Ecosystems. Ed. T. C. Hutchinson and M. Havas. Proceedings of the NATO Conference on Effects of Acid Precipitation on Vegetation and Soils, held in Toronto, Canada, May 21-27, 1978. Plenum Press, New York, 1980. 255-282.

Human use (or misuse in some cases) of forest ecosystems has caused soil acidification since prehistoric times. Emissions of sulfur dioxide and oxides of nitrogen cause a hydrogen ion input to the soil by wet and dry deposition. This input leads to substantial changes in the chemical soil



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state, especially in the uppermost soil layers. However, the ecological significance is not at all clear. Ascertaining the significance requires more data and analysis than looking only at hydrogen ions and their effect on soil acidity. With acid rain, more than 20 kilograms of nitrogen per hectare per year are being applied to lands in Central Europe. It is difficult to balance the positive impacts of the nitrogen with negative impacts of acidification to reach an overall assessment.

Ulrich, B. and J. Pankrath. "Preface," Effects of Accumulation of Air Pollutants in Forest Ecosystems. Ed. B. Ulrich and J. Pankrath. Proceedings of a workshop held at Gottingen, West Germany, May 16-18, 1982. D. Reidel Publishing Co., Dordrecht, Holland, 1983. ix-xvii.

"The problem of forest damage caused by air pollution is not new in Europe....In the neighbourhood of industries with high gaseous and dust emissions, damages have been shown to occur for a long time; these deleterious effects have influenced the growth of trees and in extreme cases have even caused their early death. All over Central Europe a scattered but immense forest damage is confirmed. In the last years a reduction in the vitality of forests has been observed especially in areas remote from industrialized regions. This exhaustion of forest ecosystems is the result of an environmental stress which has lasted already for more than several decades."

"The new complex disease of coniferous stands especially is obviously pointing towards more serious impairment. Trees, being the final link of the ecological hierarchy of a forest, are disturbed in their ecological equilibrium. The biological and/or soil buffering capacity of forest stands which normally supports the resistance of its species to different kinds of air pollution is obviously exhausted in several areas. In the Federal Republic of Germany 10 percent of the forest area exhibits deleterious impacts mainly caused by a supply of acidifying air pollutants. Whereas the symptoms of forest damage are uncontested, it is only with regard to the causes of forest injury that the opinions of forest experts strikingly disagree."

"At the moment it is a matter of fact that the impairment of air pollutants on vegetation as well as the acidification of soil signifies, according to the current state of knowledge, that toxic and root injuring aluminium ions are released. In addition, forest areas are very effectively filtering pollutants out of the air. Thus, the uptake of harmful airborne substances is increased by a significant amount if compared to the open field. This filtering effect of the canopy, called interception, works the whole year for coniferous stands; for deciduous stands it is limited to the foliage period."



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U. S. Department of Agriculture, Forest Service. Air Pollution Damage to Trees. Bulletin prepared in cooperation with the Department of Plant Pathology, Center for Air Environment Studies and Cooperative Extension Service, Pennsylvania State University. USDA Forest Service, Upper Darby, Pennsylvania, 1973.

"The impact of any air pollution problem depends on our goals for managing a particular forest. In no case is air pollution injury desirable, but under some management plans we may be able to tolerate more injury than under others. For example, severe pollution injury to a tree's leaves will decrease its ability to manufacture food and cause growth supression. The growth suppression may be more tolerable in a stand being managed as a watershed or for wildlife (except where the pollutant may cause disease in animals) than one being managed for timber."....

"Sulfur dioxide and ozone are probably the most important phytotoxic air pollutants in the Northeast. Fluorides, chiefly in the form of the gas hydrogen fluoride, also occur. Injury on conifer needles from all these pollutants is often manifested as necrosis of the needle tip or the entire needle. Ozone also causes a chlorotic mottle of needles. Most pollutants cause more specific symptoms on broadleaved trees....Air pollution injury to trees is most prevalent during inversions--meteorological conditions which do not allow pollutant-laden air to rise and disperse..."

Individual Studies

Abrahamsen. G. "Effects of Acid Precipitation on Soil and Forest: Leaching of Plant Nutrients," Ecological Impacts of Acid Precipitation, Proceedings of an International Conference, Sandefjord, Norway, March 11-14, 1980. Ed. D. Drablos and A. Tollan. SNSF Project, Oslo, Norway, October 1980. 196.

Ambient precipitation over the forest experimental site during the frost-free months of the years 1974-78 averaged about pH 4.3. Control plots receiving natural precipitation only were compared to other plots receiving artificial precipitation of pH 6, pH 4, pH 3, and pH 2. There was a tendency for leaching of calcium and magnesium to increase with greater acidity, and probably leaching of potassium increased as well. It is hypothesized that long-term, low levels of acidity will gradually leach nutrients such as calcium and magnesium, and that the tree growth-increasing effect of added inorganic nitrogen from acid precipitation (revealed in other experiments) may well prove temporary as other nutrients become limiting over time.



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Blanchard, Robert, Jay Baas, and H. Van Cotter. "Oxidant Damage to Eastern White Pine in New Hampshire," Plant Disease Reporter, Vol. 63, March 1979. 177-182.

"During the summers of 1974, 1975 and 1976, oxidant levels at three sites in New Hampshire were both sufficiently high and prolonged to cause damage to intolerant white pines....It has been demonstrated in this study that oxidant exposures within the range suggested as damaging to white pine did occur and were followed within a 10-day period by observable increases in needle damage....The similar patterns and levels of oxidant at the three recording sites suggest that atmospheric oxidants in New Hampshire are probably not from local point sources, but more likely are carried on prevailing winds from metropolitan areas to the south and west to New Hampshire."....

"It appeared that most damage to current needles was done during exposures in early summer....Physical and biological changes in the coniferous forest type in the San Bernardino National Forest could result from heavy chronic photochemical oxidant air pollution. We do not suggest the same for New Hampshire unless oxidant levels increase appreciably. White pine appears to have a wide range of tolerance to oxidants and those most severely affected do not survive long. This undoubtedly will lead to natural selection of more tolerant trees and should promote field selection of parent trees which are tolerant....However, this ignores the potential the sensitive genotypes may have for valuable silvical characteristics."

Blanpied, G. D. "Effects of Artificial Rain Water pH and Calcium Concentration on the Calcium and Potassium in Apple Leaves," Hortscience, Vol. 14, No. 6, December 1979. 706-708.

The author examines whether artificial rain water with various pH levels increases calcium leaching from apple seedlings. Data were obtained from apple tree seedlings grown in experimental plots. This study does not confirm previous reports that low pH rain leached more calcium from leaves than high pH rain. "Data collected in this study suggest that the decline of leaf calcium in New York apple leaf samples in recent years was probably not caused by acid rain."

Botkin, D. B. and J. D. Aber. Some Potential Effects of Acid Rain on Forest Ecosystems: Implications of a Computer Simulation. Paper No. BNL 50889, Brookhaven National Laboratory, Upton, New York, 1979.

The authors investigate potential effects of acid precipitation on forest productivity and species composition. Current levels of acidity in precipitation are assumed. The authors use data from 100 forest plants, and employ a stochastic simulation model to determine the direct effect of



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acid rain on mortality of leaf tissue. The simulation is driven only by the direct impact of acid rain on leaves. No damage to soil chemistry is assumed. Results show a reduction in leaf area of 0.5 percent for spruce to 5.5 percent for sugar maple, leading to no significant change in total forest biomass, nor species composition. Significant change in total productivity and relative species composition would occur only at much higher levels of acid input.

Davis, Donald and Francis Wood. "The Relative Susceptibility of Eighteen Coniferous Species to Ozone," Phytopathology, Vol. 62, No. 1, January 1972. 14-19.

"Eighteen species of 2 to 6 year old coniferous tree seedlings were exposed to 10 pphm $O_3$ for 8 hr or 25 pphm $O_3$ for 4-8 hr. Virginia pine, jack pine, European larch, Austrian pine, Scotch pine, eastern white pine, eastern hemlock, Japanese larch, and pitch pine were susceptible. Arborvitae, balsam fir, Douglas fir, white fir, red pine, black hills spruce, Colorado blue spruce, Norway spruce, and white spruce were resistant to the highest dose. The incidence of sensitive plants within susceptible species populations ranged from 6-69 percent. Variable symptom response was observed among different species, among individual plants of the same species, and among different branches and needles of the same plant. Chlorotic mottle and tip necrosis or complete needle necrosis were the most commonly observed symptoms. Susceptible species were sensitive from the 4th through 13th weeks after budbreak. Seedlings in the dormant condition were resistant."

Denison, Robert, Bruce Caldwell, Bernard Bormann, Lindell Eldred, Cynthia Swanburg, and Steven Anderson. "The Effects of Acid Rain on Nitrogen Fixation in Western Washington Conifers," Proceedings of the First International Symposium on Acid Precipitation and the Forest Ecosystem, Columbus, Ohio, May 12-15, 1975. Ed. L. S. Dochinger and T. A. Seliga. Forest Service General Technical Report NE-23. Forest Service, USDA, 1976. 933-959.

Possible effects of acid rain on fixation of atmospheric nitrogen in western Washington forests was investigated. A significant portion of nitrogen fixed in both deciduous and coniferous forests in this area comes from certain epiphytic, nitrogen-fixing lichens. Samples of these lichens were collected and soaked in the laboratory in water of pH 8, 6, 4, and 2. There was somewhat less nitrogen fixed at pH 4 than at pH 8 or 6, and much less fixed at pH 2. Sulfur dioxide concentrations are low in the Northwest, but even low concentrations appear to have an adverse effect on nitrogen fixation by limiting the distribution of these lichens. However, a much more serious threat to nitrogen fixation than acid rain is the deliberate suppression of red alder to keep it from competing with Douglas fir.



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Evans, Lance S., Nicholas F. Gmur and Filomena Da Costa. "Foliar Response of Six Clones of Hybrid Poplar," Phytopathology, Vol. 68, No. 6, June 1978. 847-856.

Experiments were conducted to ascertain the effects of simulated acid rain on six clones of hybrid poplar. After exposure to simulated acid rain at pH levels from 2.7 to 3.4, lesions of several types were produced on the foliage.

"In general, percent leaf area with lesions and percent leaves injured were similar among all six clones at all pH levels tested. At pH 2.7 up to 10.0 percent of the leaf area was injured after 5 daily exposures of 6 minutes each. Injury decreased to about 1.0 percent at pH 3.4. Lesions developed mostly near stomata and vascular tissues and occurred most frequently on leaves just prior to maximum leaf enlargement. Very young and older leaves were less affected. The results support the hypothesis that the adaxial leaf surface is the most affected after exposure to simulated acid rain."

Francis, A. J., D. Olson, and R. Bernatsky. "Effect of Acidity on Microbial Processes in a Forest Soil," Ecological Impacts of Acid Precipitation, Proceedings of an International Conference, Sandefjord, Norway, March 11-14, 1980. Ed. D. Drablos and A. Tollan. SNSF Project, Oslo, Norway, October 1980. 166-167.

The study obtained information on microbial and other activity in a forest soil in order to evaluate the impacts of deposited air pollutants on this soil. A Riverhead sandy loam soil from Long Island, New York, was used as the study medium. The natural soil, receiving only distilled water, served as a control. Other soil samples were incubated and used in the experiments in which the soil pH was adjusted to pH 7 and pH 3, values different from the natural soil pH of 4.6.

The study assessed the impact of soil acidification on rates of organic matter decomposition, nitrogen fixation by bacteria, soil enzyme activity, the distribution of soil microbial populations, and degradation of pesticides. The study concluded that, in the soil sampled, the addition of sulfuric acid to acidify the soil to pH 3 led to significant reductions in: 1) Degradation of some herbicides; 2) decomposition of leaf litter; and 3) ammonification, nitrification, and denitrification. Thus, if conditions of the experiment were to be duplicated in a forest ecosystem, nutrient recycling would be reduced.



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Haines, Bruce and George R. Best. "The Influence of an Endomycorrhizal Symbiosis on Nitrogen Movement Through Soil Columns Under Regimes of Artificial Through-fall and Artificial Acid Rain," Proceedings of the First International Symposium on Acid Precipitation and the Forest Ecosystem, Columbus, Ohio, May 12-15, 1975. Ed. L. S. Dochinger and T. A. Seliga. Forest Service General Technical Report NE-23, Forest Service, USDA, 1976. 951-961.

"Mycorrhizae often increase the uptake of nutrients by host plants. This study was designed to determine the effect of solutions having pH values of 3.0 and 2.0 on the nitrogen uptake capacity of mycorrhizal roots. The pattern of soil solution nitrogen concentrations in soil columns having five combinations of soil, tree seedlings, and endomycorrhizal fungus are reported here for three regimes in which test solutions were applied. The test solutions were: 1) artificial throughfall; 2) high ionic strength solutions of pH 5.9 and pH 3.0; and 3) artificial eastern U. S. acid rainfall. These solutions were applied to the surfaces of soil columns in plastic pipes."

"The effect of the type of solution applied and of the seedling and fungus treatment combinations on nutrient concentration were determined by monitoring changes in soil solution chemistry. Decreased concentration of nitrogen in the soil solutions in columns containing seedling and seedling + fungus compared to concentrations in columns containing soil alone is assumed to reflect nitrogen uptake by plants."

"Differences in the soil solution nutrient concentrations among the five soil-tree-fungus treatments are interpreted as nutrient uptake or loss by plants. Following application of artificial throughfall solutions, mycorrhizal roots significantly decreased the $NO_3$-N and $NH_4$-N concentrations of soil solutions. The application of high ionic strength solutions of pH 5.9 and 3.0 produced greater $NO_3$-N and $NH_4$-N concentrations in the soil solution in columns containing the mycorrhizae than in columns containing either soil alone or in columns containing soil + sweetgum seedlings. Mycorrhizal roots appeared to lose nitrogen."

"When artificial eastern U.S. acid rainfall was used to acidify the top 5 cm of soil to a soil solution pH of 2.0, $NO_3$-N concentrations were unaffected by soil-tree-fungus treatments while ammonia appeared to be excluded from soil exchange sites, apparently by H+ ions. Ammonia uptake by mycorrhizal roots was not detectable and may have been masked by high $NH_4$-N concentrations in the soil solution or inhibited by competition with H+ ions for the cation carrier sites at the nutrient "uptake surfaces" of the plants. Because soil solution nutrients not taken up by plants or by exchange sites in soil can be lost by leaching, it appears that acid rain will promote the leaching of $NH_4$-N from soil profiles but will have little influence on $NO_3$-N loss."



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Haines, Bruce, Marcia Stefani and Floyd Hendrix. "Acid Rain: Threshold of Leaf Damage in Eight Plant Species from a Southern Appalachian Forest Succession," Water, Air, and Soil Pollution, Vol. 14, 1980. 403-407.

"Eight plant species were subjected to artificial acid rains of pH 2.5, 2.0, 1.5, 1.0 and 0.5 in order to determine the threshold for and symptoms of damage." The plants were fireweed, locust, pine, oak, hickory, tulip tree, maple, and dogwood. "Droplets of pH 2.0 produced brown necrotic spots on all species except pine, while droplets of pH 1.0 produced necroses on leaves of all species examined. The size of necrotic spots increased with increasing acidity....Results of this study suggest that a 10-fold increase in acidity from pH 3.2 to 2.2 in a single spring or summer storm could bring damage or death to mature leaves of dominant flowering plants in the Southern Appalachians."

Hovland, J. "The Effect of Artificial Acid Rain on Respiration and Cellulase Activity in Norway Spruce Needle Litter," Soil Biology and Biochemistry, Vol. 13, July 1981. 23-26.

Cellulase and respiration are used as dependent variables to evaluate the impact of acid rain on Norway spruce needle litter. The author collected data from 12 plots (3 replications) using 4 water treatments with a pH of 2.5, 3.0, 4.0, 6.1, respectively, and then employed multiple regression. Results of the regression suggest that, under natural conditions, acid precipitation has a small adverse effect on the biochemical activity which produces cellulase and carbon dioxide in coniferous litter.

Johnson, Arthur J. "Red Spruce Decline in the Northeastern U. S.: Hypotheses Regarding the Role of Acid Rain," Journal of the Air Pollution Control Association, Vol. 33, No. 11, November 1983. 1049-1054.

"Red spruce have died in abnormal numbers in the high elevation forests of New York and New England during the past two decades, while spruce in the southern Appalachians remain healthy. Investigations of insect damage, fungal pathogens, successional dynamics, competitive status, climate and weather patterns, and possible pollutant effects indicate that the decline was triggered by abiotic stress during the dry years of the 1960's. Tree response, as recorded in the pattern of annual rings, and the wide range of soil conditions in which spruce are declining, suggest drought or dry summers as key factors. Hypotheses regarding the role of acid deposition-induced stress have been offered, but at present there is not evidence which clearly links acid deposition to spruce decline. Indirect effects of acid deposition on soils, direct effects of acid deposition on foliage, and interactions of acid deposition and drought stress are possible but unproven pathways by which acid deposition could be involved."....



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"The characteristics of the high elevation forests of eastern North America cause them to be receptors of high rates of acid and trace metal input. No other extensive forested areas are subject to as intensely acid moisture, as heavy deposition, and as heavy trace metal deposition. The vulnerability of those forests to the airborne pollutants has not been documented, but must be suspected."

"In reviewing the data currently available, there are pathways by which acid deposition could contribute to spruce decline, but the framework for aluminum toxicity proposed by Ulrich is not consistent with the data generated in U. S. forests. There is reasonable evidence that the dry period of the early 1960's triggered the decline, but it is not clear whether drought alone was sufficient to cause the initiation of the decline, or whether other pollutant stresses were involved. Similarly, the current level of information available on ecosystem level nutrient cycling processes is insufficient to allow prediction of whether the montane boreal forests will 'unravel' as a result of pollutant inputs."

Johnson, Arthur H., Deborah G. Lord, and Thomas G. Siccama. "Red Spruce Dieback in Vermont and New Hampshire: Is Acid Precipitation a Contributing Stress?" Acid Rain: A Water Resource Issue for the 80's, International Symposium on Hydrometeorology, June 1982. Ed. R. Herrman, and A. Ivan Johnson. American Water Resources Association, Bethesda, Maryland, 1983. 63-67.

"A dieback of red spruce (Picea rubens) has been quantitatively documented in the high elevation boreal forest of Vermont, and observed in New Hampshire and New York. No primary pathogens or obvious abiotic factors appear to be responsible for the dieback. The boreal forest of the Green and White Mountain peaks is above cloud base for extended periods (800-1600 hours per year), and cloud moisture is very acid (average pH approximately 3.7). A study of foliar, root, and soil chemistry in healthy and declining stands in Vermont and New Hampshire leaves open the possibility of acid rain-induced stress due to effects on foliage or, less likely, effects due to high levels of root aluminum."....

[The authors] "regard these data as inconclusive, but a useful first step in defining directions for future research. A better understanding of soil-plant nutritional relationships is needed, and data from controlled experiments would be helpful in trying to explain the differences in aluminum, sulfur, and nitrogen. No conclusions regarding the presence or absence of acid precipitation-induced stress are warranted; however, the data presented suggest that the possibility of a biogeochemical link between acid precipitation and spruce dieback exists. It is important to pursue other mechanisms which could be important stresses. Biotic agents such as primary root pathogens have not been thoroughly studied. Stress from oxidant pollutants alone or in combination with acid precipitation remains uninvestigated."



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Johnson, A. H., T. G. Siccama, D. Wang, R. S. Turner, and T. H. Barringer. "Recent Changes in Patterns of Tree Growth Rate in the New Jersey Pinelands: A Possible Effect of Acid Rain," Journal of Environmental Quality, Vol. 10, No. 4, October-December 1981. 427-430.

"Increment cores from pitch pine (Pinus rigida Mill.), shortleaf pine (Pinus echinata Mill.), and loblolly pine (Pinus taeda L.) indicate an abnormal decrease in growth rates over the past 25 years. Stream pH, a reliable index of precipitation pH, and a strong statistical relationship between stream pH and growth rates, suggests that acid precipitation may have been a growth-limiting factor for the past two decades. Other factors such as drought, fire, pests, and atmospheric oxidants do not appear to be responsible for the two decades of abnormally slow growth."....

"The characteristics of the decrease in growth are unique to the 1955-1979 period. No other events are recorded in the tree ring record (which dates back to 1852) that are as widespread, long-lasting, and severe in their effects. Clearly there is something adversely affecting the growth of pitch, shortleaf, and loblolly pine in southern New Jersey. The apparently different behavior of white pine is presently inexplicable.

Without data from controlled experiments, a definite link between acid precipitation and tree growth cannot be made. However, the timing and uniqueness of the shift in growth patterns, the concomitant shift in factors related to growth patterns, the clear relationship between growth rate and stream pH indicate that acid rain merits strong consideration as a factor suppressing tree growth in the Pinelands."

Johnson, D. W., D. W. Cole, and S. P. Gessel. "Acid Precipitation and Soil Sulfate Adsorption Properties in a Tropical and in a Temperate Forest Soil," Biotropica, Vol. 11, No. 1, 1979. 38-42.

"Atmospheric sulfuric acid inputs and leaching in a tropical and temperate forest are compared. In both cases, [the hydrogen ion] is mostly removed in the forest canopy. The tropical forest appears to be accumulating sulfate whereas the temperate forest is near steady-state. The tropical soil has a high capacity permanently to retain sulfate, which is probably related to its high sesquioxide content. It is proposed that the high sesquioxide content of the tropical soil renders it very resistant to leaching by atmospheric sulfuric acid inputs."....

"Since a smaller proportion of the sulfate [at the temperate soil site] is permanently adsorbed, one would hypothesize that much of the sulfate entering this soil can eventually leach through, even though it is adsorbed."



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Kercher, J. R., and H. C. Axelrod. "Modeling the Impact of $SO_2$ Pollution on the Community Structure and Succession in a Coniferous Forest of the Western U. S. A.," Ecological Impacts of Acid Precipitation, Proceedings of an International Conference, Sandefjord, Norway, March 11-14, 1980. Ed. D. Drablos and A. Tollan. SNSF Project, Oslo, Norway, October 1980. 174-175.

The authors describe and use a long-term forest simulation model to project the future impact of sulfur dioxide pollution on a western forest of Ponderosa pine and six other tree species. The model simulates the interaction over time of tree growth, competition among the seven tree species studied, influence of fire, impact of sulfur dioxide, and other factors. The authors use data from other experiments showing the growth-inhibiting response of each tree species to sulfur dioxide pollution. The simulation model projects that, over a 500 year period, the effect of sulfur dioxide pollution would result in a 10 percent growth reduction for Ponderosa pine, and also a growth reduction ranging up to 18 percent for Douglas fir, from the baseline growth which would occur without the pollution. Species composition of the forest would shift away from these two species somewhat to the favor of white fir.

Lee, Jeffrey and David E. Weber. "Effects of Sulfuric Acid Rain on Major Cation and Sulfate Concentrations of Water Percolating Through Two Hardwood Forests," Journal of Environmental Quality, Vol. 11, No. 1, 1982. 57-64.

In order to document and quantify ecosystem response to the onset of acid precipitation, simulated sulfuric acid ($H_2SO_4$) rain was applied to model forest plots of sugar maple and red alder. Water samples were collected above and below the canopy, below the litter layer, and from 20-centimeter and 1-meter depths below the surface of the soil. "Results showed that a hardwood canopy and litter layer can alter the input of chemicals to the soil from acid rain, that the relative sensitivity of ions to mobilization by acid rain is not the same for all components of an ecosystem, and that acid rain can alter the chemical composition of water within the root zone within a few years, even if the soil is a strong sulfate absorber."

Malanchuk, John L., Jeffrey I. Jones, Patricia M. Rocchio, James R. Rhea, and Anthony J. Ranalli. "Sensitivity of Adirondack Ecosystems to Acid Deposition," Northeastern Environmental Science, Vol. 1, No. 3/4, 1982. 205-210.

"Nine sites located throughout the Adirondack Mountains were investigated to determine potential sensitivity to acid deposition. Basic soil properties, litter production, and decomposition rates were measured for all sites. Litter production and decomposition were highest at Lake Durant. Litter production at the Old Forge site was lowest while the lowest decom-



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position rate was observed at the Speculator site. The low values for percent base saturation and high values for exchangeable acidity obtained in this study suggest the potential sensitivity of the Adirondack region to acid deposition. The results also indicate a high degree of variability among all nine sites for the parameters investigated."

Puckett, L. J. "Acid Rain, Air Pollution and Tree Growth in Southeastern New York," Journal of Environmental Quality, Vol. 11, No. 3, 1982. 376-381.

The author contends that it is feasible to use dendroecological analysis to detect changes in tree growth-climate relationships that might have resulted from chronic exposure to acid rain and its components. "Tree ring indices of white pine, eastern hemlock, pitch pine and chestnut oak were regressed against orthogonally transformed values of temperature and precipitation in order to derive a response-function relationship."

"Results of the regression analysis for three time periods suggest that the relationship of tree growth to climate has been altered. Statistical tests of the temperature and precipitation data suggest that this change was nonclimatic. Temporally, the shift in growth response appears to correspond with the suspected increase in acid rain and air pollution in the Shawangunk Mountain area of southeastern New York in the early 1950's. This change could be the result of physiological stress induced by components of the acid rain-air pollution complex, causing climatic conditions to be more limiting to tree growth."

Roberts, T. M., T. A. Clarke, P. Ineson, and T. R. Gray. "Effects of Sulfur Deposition on Litter Decomposition and Nutrient Leaching in Coniferous Forest Soils," Effects of Acid Precipitation on Terrestrial Ecosystems. Ed. T. C. Hutchinson and M. Havas. Proceedings of the NATO Conference on Effects of Acid Precipitation on Vegetation and Soils, held in Toronto, Canada, May 21-27, 1978. Plenum Press, New York, 1980. 381-393.

Episodes of artificial acid precipitation with a pH around 3.0, applied to plots in a pine forest in central England, produced small increases in the rate of pine litter decomposition compared with rates associated with an artificial precipitation of distilled water at pH 5.6 on control plots. The precipitation which was acidic released nitrogen somewhat more rapidly into solution than the nonacidic precipitation. The sulfuric acid leaching through the organic soil horizons was readily fixed by the mineral horizons. However, the effects on general forest productivity were not assessed. The acid applications did not change the pH of the organic horizons of the soils in the field plots, which remained around pH 4.0-3.5.



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Singh, B. R. "Distribution of Total and Extractable Sulfur and Adsorbed Sulfate in Some Acid Forest Soil Profiles of Southern Norway," Acta Agriculturae Scandinavica, Vol. 30, No. 4, 1980. 357-363.

"Since many soils are known to adsorb sulfate, a quantitative estimation of sulfate adsorption capacities of different soils is important from the point of view of sulfate storage in the soil profile and leaching losses of sulfate and associated cations to natural water courses."....

"The range of sulfate adsorption capacities has not been established, but it is generally agreed that soils containing large amounts of free aluminum and iron oxides and 1:1 type of clay minerals have a very large capacity to adsorb sulfate as compared to soils containing 2:1 type of clay minerals. Although it is reported that relatively high amounts of sulfate (3 to 4 grams per square meter) are added annually to the soils of southern Norway through dry deposition, snow, and rain, information on the fate of this deposited sulfur is scanty. The present investigations were planned to study sulfate sorption and some associated factors affecting this phenomenon in acid forest soils."....

"In conclusion it can be stated that of the soil properties tested, dithionite-citrate extractable aluminum and iron fractions are the most important adsorber of applied sulfate, and hence sulfate in the soils studied. These may be responsible for the differences in sulfate adsorption among profiles and also among horizons within a profile, although characteristics such as organic carbon, pH, and clay contents may also have played a role in altering the effectiveness of aluminum and iron oxides."

Skelly, John M., Boris I. Chevone, and Yaw-Shing Yang. "Effects of Ambient Concentrations of Air Pollutants on Vegetation Indigenous to the Blue Ridge Mountains of Virginia," Acid Rain: A Water Resources Issue for the 80's, International Symposium on Hydrometeorology, June 1982. Ed. R. Herrmann and A. Ivan Johnson. American Water Resources Association, Bethesda, Maryland, 1983. 69-73.

"Vegetation indigenous to the Shenandoah National Park (SNP) and Blue Ridge Mountains of Virginia has been exposed to phytotoxic concentrations of oxidant air pollution, primarily ozone, over the past several years. Exposure of vegetation to episodic ozone incursions has resulted in visible symptom expression on several native plant species. Longer term, low dosage exposures typically recorded throughout the summer oxidant season have been demonstrated to reduce foliar biomass production of native forbes, grasses, and sedges via an air pollutant exclusion chamber system in the Big Meadows area of the SNP. Seedling height growth of several forest tree species was also adversely affected by ambient oxidant concentrations. Monitoring data for ozone and sulfur dioxide at SNP from 1979-1981 have demonstrated that ozone was present in eight-hour (1100-1800 EST) average concentrations of



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"0.023 to 0.059 ppm ozone during April through September; hourly average sulfur dioxide concentrations rarely exceeded 0.006 ppm. Analysis of weekly rainfall samples has also been conducted since November of 1978 with the lowest pH rainfall recorded of 3.39. The average pH of all weekly samples is about 4.35. No effects on vegetation in the Blue Ridge Mountains have been ascribed to acidified rainfall."....

...."At present, only ambient ozone concentrations have been shown to reduce growth and productivity of native plant species. However, the potential exists for interactive effects of acidic precipitation and ozone and additional research is required to determine if such effects may be occurring."

Stottlemyer, J. Robert. "Variation in Ecosystem Sensitivity and Response to Anthropogenic Atmospheric Inputs, Upper Great Lakes Region," Acid Rain: A Water Resources Issue for the 80's, International Symposium on Hydrometeorology, June 1982. Ed. R. Herrmann and A. Ivan Johnson. American Water Resources Association, Bethesda, Maryland, 1983. 79-83.

"Generalizations regarding ecosystem sensitivity to the direct and indirect impacts of anthropogenic atmospheric inputs will be difficult in this glaciated region because of the geological variation. The interaction of precipitation amount, vegetation type, and the presence or absence of alkaline glacial tills result in a complex mosaic with very sensitive ecosystems intermixed with more resistant ecosystems."

Strand, Lars. "The Effect of Acid Precipitation on Tree Growth," Ecological Impacts of Acid Precipitation, Proceedings of an International Conference, Sandefjord, Norway, March 11-14, 1980. Ed. D. Drablos and A. Tollan. SNSF Project, Oslo, Norway, October 1980. 64-67.

It is not possible by the method of tree ring analysis employed in this study to find clear evidence that acid precipitation has had an effect on tree growth. The study analyzed tree ring data from sample trees of Norway Spruce and Scots pine from 6,150 sample plots, and related these data over a 60-year period to pre-existing observations of rainfall, its acidity, and other climatic variables. Variations in ring growth could not be clearly related to variations in acidity. Future investigation might take another approach, that of taking a relatively small number of experimental plots and monitoring tree growth and many other variables in detail.



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Tamm, Carl Olof and Ellis B. Cowling. "Acid Precipitation and Forest Vegetation," Proceedings of the First International Symposium on Acid Precipitation and the Forest Ecosystem, Columbus, Ohio, May 12-15, 1975. Ed. L. S. Dochinger and T. A. Seliga. Forest Service General Technical Report, NE-23, Forest Service, USDA, 1976. 845-855.

"The effects of acidic precipitation on plants are only one facet of the much larger subject of atmosphere-plant-soil interactions....[T]he effects of a given 'acid rain' or a prevailing condition of 'acidic rains' are very complex, variable in time, and involve significant interactions which are only partially understood."

Some of the potential or hypothetical effects of acidic precipitation on vegetation are discussed. The effects are classified as either direct or indirect.

"Direct effects

1. Damage to protective surface structures such as cuticle....
2. Interference with normal functioning of guard cells....
3. Poisoning of plant cells after diffusion of acidic substances through stomata or cuticle....
4. Disturbance of normal metabolism or growth processes without necrosis of plant cells....
5. Alteration of leaf and root-exudation processes....
6. Interference with reproduction processes....
7. Synergistic interaction with other environmental stress factors...."

"Indirect effects

1. Accelerated leaching of substances from foliar organs....
2. Increased susceptibility to drought and other environmental stress factors....
3. Alteration of symbiotic associations....
4. Alteration of host parasite interactions...."

While there is some evidence to suggest each of the above as hypotheses, there is not yet enough evidence to regard the hypotheses as proven.

Tamm, Carl Olof, and Gunnar Wiklander. "Effects of Artificial Acidification with Sulfuric Acid on Tree Growth in Scots Pine Forest," Ecological Impacts of Acid Precipitation, Proceedings of an International Conference, Sandefjord, Norway, March 11-14, 1980. Ed. D. Drablos and A. Tollan. SNSF Project, Oslo, Norway, October 1980. 188-189.

Plots in a pine stand established in 1953 were irrigated regularly between 1971-76 by ground application with water of three different degrees of acidity, each level of acidity being successively higher than the acidity of precipitation falling naturally on the control plot. Consistent with previous experimental findings, the application of additional acid



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(without adding supplementary fertilizer) had the immediate effect of increasing the available supply of nitrogen to the trees by damaging other vegetation and biota on and under the forest floor. Competition for nitrogen was thus reduced, and the trees receiving acid thus showed greater growth than the trees on the control plot. However, this may be only a short-term effect, drawing upon the potential stock of nitrogen in the forest floor. On other plots, which received both supplementary fertilizer as well as the three increasing levels of acid, the plots receiving the largest amounts of acid (plus the fertilizer) showed less tree growth than the control plots receiving no additional acid or fertilizer. At this very high level of acidification, therefore, decreases in growth due to acidity emerge, although not elsewhere in the experiment. Nevertheless, this very high level of acidification was greatly in excess of the acidity in rainfall falling on the plots naturally.

Tamm C., G. Wiklander and B. Popovic. "Effects of Application of Sulfuric Acid to Poor Pine Forest," Water, Air, and Soil Pollution, Vol. 8, 1977. 75-87.

The authors identify effects of acid treatments of forests in Lisselbo and Norrliden, Sweden, using sulfuric acid and fertilizer. At both sites, nitrogen limited forest growth. When sulfuric acid was applied, much of the ground vegetation was lost. No negative effects on the growth of trees were detected during the seven year span of the experiment. However, experiments showed that adding sulfur or sulfuric acid to the soil did adversely affect biological processes in the soil, especially the recycling of nitrogen.

Turner, John and Marcia J. Lambert. "Sulfur Nutrition of Forests," Atmospheric Sulfur Deposition: Environmental Impact and Health Effects. Ed. D. Shriner, C. Richmond, and S. Lindberg. Proceedings of the Second Life Sciences Symposium, Gatlinburg, Tennessee, October 14-18, 1979. Ann Arbor Science, Ann Arbor, Michigan 1980. 321-324.

"Sulfur is an essential major tree nutrient and the biochemical relationship between sulfur and nitrogen in plant proteins dictates that neither element can be adequately assessed without reference to the other....Sulfur toxicity in trees is confined to limited areas where concentrations of sulfur dioxide are high, whereas in most situations sulfur inputs are as sulfate, and damage symptoms are not produced. A comparison of various conifer species indicated that species native to coastal situations, with high maritime sulfur inputs, were more elastic in their utilization of sulfur than species native to inland locations. Additions of nitrogen to forest stands results in the incorporation of sulfate sulfur into organic forms, and thus the sulfate cycle in forest ecosystems is regulated to a large extent by nitrogen status and nitrogen cycling."



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Tveite, Bjorn. "Effects of Acid Precipitation on Soil and Forest: Tree Growth in Field Experiments," Ecological Impacts of Acid Precipitation, Proceedings of an International Conference, Sandefjord, Norway, March 11-14, 1980. Ed. D. Drablos and A. Tollan. SNSF Project, Oslo, Norway, October 1980. 206-207.

Based on field experiments lasting from 4 to 7 years, irrigating different tree species with water of varying degrees of acidity showed that the species in the experiment responded as follows to the "artificial" acidification of groundwater: (1) Lodgepole pine--no clear effects of acid treatments; (2) Norway spruce--growth of treated trees reduced slightly compared to nontreated (nonacidified) tree stands; (3) Scots pine saplings--increased acidity tended to increase height and diameter; (4) Scots pine mature trees--no effects of increased acid; (5) Birch--height growth stimulated by increased acidity.

Tveite, Bjorn, and Gunnar Abrahamsen. "Effects of Artificial Acid Rain on the Growth and Nutrient Status of Trees," Effects of Acid Precipitation on Terrestrial Ecosystems. Ed. T. C. Hutchinson and M. Havas. Proceedings of the NATO Conference on Effects of Acid Precipitation on Vegetation and Soils, held in Toronto, Canada, May 21-27, 1978. Plenum Press, New York, 1980. 305-318.

"This paper gives results of growth measurements in four field irrigation experiments with artificial acid rain within southern Norway. Foliar analyses were carried out in three of the experiments. Height and diameter growth were stimulated by increased 'rain' acidity in a Scots pine sapling stand. The reason for this is probably increased nitrogen uptake from the soil. A beneficial effect of sulfur application either alone, or in combination with increased nitrogen uptake is also possible. In the other experiments no treatment effects on height or diameter growth were found..."

"Acid precipitation involves deposition of relatively large amounts of nitrogen. The annual deposition of inorganic nitrogen in southern Norway is of the order 7-15 kg per ha. The sulfur deposition is even slightly larger. [Possibly,] [t]his deposition of nitrogen and....sulfur, is likely to increase short-term forest productivity. The long-term effect of an increased loss of metal cations is hard to predict. These nutrients are generally in surplus at present and little is known about the effect of acid precipitation on the mobilization of the same nutrients through weathering..."



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Ulrich, B., R. Mayer, and P. K. Khanna. "Chemical Changes Due to Acid Precipitation in a Loess-Derived Soil in Central Europe," Soil Science, Vol. 130, No. 4, October 1980. 193-199.

"In a stand of European beech trees in the Solling highlands, Federal Republic of Germany, we followed the effect of acid precipitation on chemical soil state and the ion fluxes in the ecosystem between 1966-1979. As indicated by increasing aluminum concentration in the soil solution and an increase in organic matter storage in the forest floor, for example, the soil shifted during the measuring period from one state toward another one."

"During this transition, the acid precipitation has induced soil internal hydrogen ion production, partly by accumulation of organic matter poor in nitrogen, and partly by a probable change in the type of nitrogen nutrition. Two-thirds of the hydrogen ion buffering is due to the dissolution of polumeric hydroxoaluminum, resulting in the formation of solid $AlOHSO_4$ and the leaching of aluminum ions. There are indications that the aluminum concentration in soil solution reaches toxic levels for the stand. The findings may have serious consequences for forestry in central Europe."

West, D. C., S. B. McLaughlin and H. H. Shugart. "Simulated Forest Response to Chronic Air Pollution Stress," Journal of Environmental Quality, Vol. 9, No. 1, 1980. 43-49.

"A mathematical model (FORET) previously developed to examine the successional dynamics of eastern deciduous forests was applied to the study of long-term interactions of air pollution stress and forest community dynamics. Differential levels of growth reduction were applied to trees in three pollution sensitivity classes to simulate changes in biomass of both individual species and the entire forest stand."

"The response of individual species in a forest stand may differ markedly from results predicted on the basis of responses determined in the absence of plant competition. Some species may show growth enhancement in spite of pollution stress, since they may gain a competitive advantage as a result of greater impacts on other species with which they interact in the successional process. Other species may experience much greater than anticipated beneficial or injurious impacts due to reduced competitive potential. The results presented are not intended to be final quantitative answers but are presented to stress important considerations to be addressed in predicting the responses of a forest to stresses such as air pollution."



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Wood, Tim. "Short Term Effects of a Simulated Acid Rain Upon the Growth and Nutrient Relations of Pinus Strobus L.," Proceedings of the First International Symposium on Acid Precipitation and the Forest Ecosystem, Columbus, Ohio, May 12-15, 1975. Ed. L. S. Dochinger and T. A. Seliga. Forest Service General Technical Report NE-23, Forest Service, USDA, 1976. 815-825.

"[T]he short term effects of simulated acid rain (pH range 5.6-2.3) upon the growth and nutrient relations of Eastern White Pine seedlings grown in a sandy loam soil were examined....'Rains' were solutions of sulfuric, nitric and hydrochloric acids....Marked soil pH declines were measured after 20 weeks of treatment at pH 2.3. Leaching of Mg and Ca steadily increased with 'rain' acidity through the pH range 5.6-2.3. K losses did not increase until the 'rain' pH was lowered to 3.0 and 2.3....Greatly depleted levels of exchangeable cations were found at pH 2.3. Seedling productivity increased significantly with rainwater acidity. Lowest growth was measured at pH 5.6, and the greatest growth at pH 2.3. Nitrate fertilization probably caused this trend. Nitrogen can only stimulate growth when supplies of available cations are adequate. Increased leaching losses of K, Mg, and Ca and the declines in exchangeable....cations measured at pH 2.3 raise questions regarding how long declining supplies of available cations might support growth. The accelerated productivity noted at pH 2.3 may be a short term phenomenon."

Wood, T. and F. H. Bormann. "Increases in Foliar Leaching Caused by Acidification of an Artificial Mist," Ambio, Vol. 4, 1975. 169-173.

"1) This study was undertaken to investigate the effects of acidified rain on the foliar leaching of nutrient cations from pinto bean and sugar maple seedlings."

"2) Increases in foliar losses of potassium, magnesium and calcium ions from both species were associated with increases in the acidity of an artificial mist."

"3) At pH's of 3.0 and below, tissue damage, presumably caused by high concentrations of hydrogen ions, may have contributed greatly to the increased cation losses found at these levels."

"4) At pH's of 3.3 and above, although no tissue damage was observed, increases in the foliar leaching of potassium,, magnesium and calcium ions from pinto beans were found. Sugar maple lost more calcium ions at pH 3.3 than at pH's 4.0 and 5.0, but losses of potassium ions and magnesium ions were not affected at these acidity levels."



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"5) Despite the absence of statistically significant hydrogen ion uptake by the leaves, increased cation losses in the absence of visible tissue damage are evidence in support of a) hydrogen ion exchange as a mechanism for foliar leaching, and b) the hypothesis that increased rainwater acidity, regardless of the mechanism, may be accelerating foliar leaching of nutrient cations from exposed plants."

"6) A comparison of our experimental leaching rates with natural losses observed under a hardwood canopy indicates difficulties in quantitatively translating laboratory results to field conditions. However, we feel that the observed increases may be of importance in qualitative considerations of nutrient cycling in forest and agricultural ecosystems since precipitation with pH's of 4.0 and less have been falling on northern Europe and the northeastern U.S. for at least the past two decades."



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## GLOSSARY

Aerosol - A suspension in a gas of very small solid particles or liquid mist

Ammonia - ($NH_3$) A gas, compounds of which provide plant food nitrogen

Ammonium - ($NH_4$) A salt, compounds of which provide plant food nitrogen

Anion - A negatively charged ion (see "ion" below)

Atmospheric residence time - The time during which an identifiable substance (gas, liquid, or solid) emitted to the atmosphere remains in the atmosphere before falling back to earth

Atmospheric transformation - Photochemical and other chemical reactions which occur in the atmosphere

Buffered soil - A soil underlain by or derived from calcareous rocks, usually limestone; therefore, a soil able to neutralize large quantities of acid

Ca - Calcium

Carbon dioxide - ($CO_2$) A gaseous compound of carbon and oxygen, a major contributor to photosynthesis and plant growth

Cation - A positively charged ion, such as an ion of hydrogen, units of which are the measure of acidity

Heterotrophic - Obtaining food from organic material. Heterotrophic micro-organisms break down organic matter into inorganic substances which plants can use as nutrients.

Ion - An electrically charged atom or group of atoms; cation or anion

K - Potassium

Leaching - Losing soluble minerals through the filtering action of water

Mg - Magnesium

N - Nitrogen

Nitrate - ($NO_3$) A salt of nitric acid, readily soluble in water; a source of nitrogen for plant growth

Nitric acid - ($HNO_3$) Forms in the atmosphere; one of the acid rain acids.

Oxidant - An oxidizer or oxidizing agent; a substance which unites readily with oxygen, or causes another to unite with oxygen



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Oxides - Compounds of oxygen with some other element(s), as "oxides of nitrogen"

Ozone - ($O_3$) A triatomic form of oxygen which is a bluish, irritating gas of pungent odor. It is formed in the atmosphere by photochemical reaction, and is a major agent in the formation of smog. It is an oxidizing agent, one of the two major oxidants (with PAN) contributing to air pollution.

P - Phosphorus

PAN - Peroxyacetylnitrate; an oxidant or oxidizing agent. One of the two major photochemical oxidants (with ozone) contributing to air pollution.

pH - Potential hydrogen, a measure of hydrogen ion concentration and a measure of acidity or alkalinity. Acidity of precipitation is measured on the pH scale, according to which values below about pH 7.0 are acid, values above pH 7.0 are alkaline. The lower the value below pH 7.0, the greater the acidity. For example, a drop in value from pH 5.0 to pH 4.0, or each whole number decrease, means a tenfold increase in acidity, since the pH scale is logarithmic.

Photochemical - Of or resulting from the effect of light in producing a chemical reaction

S - Sulfur

Sulfate - ($SO_4$) A salt of sulfuric acid, readily soluble in water; also, a product of further chemical reaction of $SO_2$ with atmospheric oxygen

Sulfuric acid - ($H_2SO_4$) Forms in the atmosphere; one of the acids of acid rain

Sulfur dioxide - ($SO_2$) A gaseous compound of sulfur and oxygen; a major component of air pollution

Weathering - Losing components of soil or rock by exposure to wind erosion and/or by chemical reaction with the atmosphere



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## PLANT INDEX

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